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INVESTIGATION OF COMMERCIAL MASONRY CEMENTS

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ABSTRACT

Information on the properties of masonry cements being very meager, or at least, in general, not comparable, the investigation reported here was initiated. Forty-one commercial masonry cements were studied with respect to chemical composition, fineness, weight per unit volume, volumetric flow of the neat pastes, and bulk specific gravity, while mortars made from those cements were studied with respect to resistance to deformation, water-retaining capacity, volume, yield, linear changes, compressive and transverse strength, efflorescence, durability when subjected to cycles of freezing and thawing, and absorption.

It was found that the cements could be classified as hydraulic limes, hydrated limes, natural cements, blast-furnace-slag cements containing various additions, several cements whose composition could not be positively determined, or portland cements with and without admixtures, the quantities of which varied from small amounts to amounts larger than the quantity of portland cement. About half of those studied contained water-repellent additions.

The physical properties of the mortars made from the cements also varied over a wide range. For example, the weight per cu. ft. of cements varied from 39.7 to 89.9 lb. The compressive strength of the mortars when tested at 28 days ranged from 50 to 3,650 lb/in.[2] The addition of water-repellent material strikingly affected the properties of mortars made from cements to which such additions had been made. The workability particularly seemed to be increased, due to the incorporation of air in the mortar during mixing, brought about by the water-repellent additions acting as emulsifying agents.

A discussion of the essentials of a specification for masonry cement is presented.

CONTENTS

I. INTRODUCTION

Information on the properties of many of the cements used principally in masonry being either very meager or, in general, not comparable, the present investigation was initiated. Forty-one such cements were collected from manufacturers and studied according to the outline under sections II, III, and IV of the table of contents.

II. THE CEMENTS

1. CHEMICAL COMPOSITION

The chemical analyses are presented in table 1. These cements may be classified as hydraulic or hydrated limes (indicated in the table as HL), natural cements (N), portland cements or portland cement with small quantities of admixtures (P), portland cements with the addition of hydrated lime (PL), portland cement mixed with various unidentified materials (PM), blast furnace slags with various additions (S), and 2 whose identity could not be established (U).

Water-repellent materials were present in about half of the cements as shown in table 1. These materials were apparently added to the cements for increasing either or both the water-repellent or plastic properties of mortars made from them. The amount of material identified as a petroleum product varied from 0.2 to 0.5 percent; that as fatty acid with three exceptions was less than 0.10 percent. The 3 exceptions contained 0.14, 0.22, and 0.48 percent. Numbers 34 and 39 contained water-repellent materials, but in such small quantities that they could not be identified.

The "free lime" determination as carried out by the ammonium acetate method, shows that not only CaO but $Ca(OH)_2$ serves in a way to indicate in certain cases the amount of hydrated lime added. Large proportions of "insoluble" in some of the portland cements suggest that siliceous material was added to improve some of the desirable characteristics, such as workability, water retention, etc. A high ignition loss with low "free lime" indicates the use of limestone dust as a plasticizing agent.

TABLE 1.—*General nature, analyses, fineness, and weights per cubic foot of the cements*

Identification number	General nature [a]	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	SO_3	Ignition loss	Insoluble	"Free lime"	Lb/ft^3 rodded	Lb/ft^3 loose	Percent retained 325 sieve	Percent retained 450 sieve	Water repellent additions [b]
1	PN	22.1	1.8	8.1	33.5	20.6	0.04	13.9	1.6	13.3	62.2	56.0	17.7	28.3	a
2	PL	12.5	1.2	4.3	59.3	1.0	0.6	20.8	7.0	19.9	56.5	49.9	------	------	e
3	HL	17.3	1.6	6.7	58.9	1.8	0.5	12.6	1.3	19.2	50.3	42.1	11.0	20.0	e
4	S	32.2	0.8	11.3	49.5	2.0	2.1	2.3	0.7	10.9	66.4	54.6	8.1	35.3	e
5	PL	12.8	1.9	4.3	56.4	14.6	1.2	8.2	0.2	21.1	47.7	38.5	------	------	e
6	PM	28.6	7.8	7.4	44.8	3.4	1.2	8.4	16.8	0.2	73.1	64.6	------	------	e
7	N	24.4	2.6	6.3	36.0	21.2	1.9	7.8	10.8	1.7	63.0	55.0	15.3	20.5	b
8	PM	24.7	3.0	7.1	59.3	0.8	3.7	1.4	0.2	1.0	72.0	63.4	13.2	23.4	a
9	PM	19.5	2.5	6.9	48.7	1.2	1.2	20.1	4.7	0.8	67.7	59.5	18.1	33.0	e
10	PM	15.5	1.8	3.3	56.9	4.4	1.1	16.9	2.8	4.5	70.3	61.4	17.3	29.2	b
11	N	24.1	1.2	9.7	34.5	22.6	3.0	4.7	10.8	0.9	59.0	51.7	10.4	22.1	b
12	N	24.7	3.5	5.8	49.8	6.3	1.6	7.5	10.5	4.5	65.1	55.8	23.2	38.1	e
13	N	20.6	2.5	5.1	36.2	23.9	2.3	6.4	7.5	5.0	56.2	47.5	10.4	21.0	b
14	PM	12.1	0.5	3.1	61.2	3.3	1.3	18.6	0.3	13.0	63.4	55.6	11.2	20.4	b
15	S	33.0	0.9	9.7	49.9	2.0	2.7	1.8	3.2	6.2	71.7	63.1	17.3	37.2	b
16	PN	19.5	2.4	7.8	52.7	2.7	1.7	12.5	5.9	11.0	61.2	55.2	5.3	11.3	b
17	PL	7.7	1.4	2.5	53.3	20.8	0.7	13.6	0.3	27.5	43.4	38.2	23.1	28.2	e
18	P	21.8	0.4	1.3	71.4	1.8	0.7	2.8	0.4	16.7	64.7	55.8	9.2	31.3	e
19	P	24.2	0.4	4.7	65.3	1.4	1.9	2.4	0.3	0.2	87.7	80.3	10.3	25.4	b
20	P	21.9	0.5	5.8	63.0	4.4	1.9	2.7	0.5	3.1	89.9	80.6	26.2	46.2	b
21	PL	11.5	1.8	3.0	66.4	4.1	0.2	13.1	0.6	29.3	41.8	34.8	9.1	20.3	e
22	PM	13.5	1.8	4.4	52.5	11.8	1.2	14.7	5.6	10.7	59.2	51.6	21.0	27.4	e
23	S	34.2	2.0	10.7	46.7	2.9	0.1	2.9	0.6	6.2	66.9	61.1	12.4	32.1	e
24	S	32.2	2.3	9.9	43.5	5.2	3.6	2.9	8.4	0.5	65.3	57.2	5.4	17.1	b
25	PL	8.9	1.6	3.5	53.1	9.6	0.9	22.6	0.9	7.4	63.5	57.2	20.4	33.5	a
26	PL	10.3	1.5	2.8	51.2	21.3	1.3	12.3	4.3	27.5	49.4	43.8	20.3	34.2	e
27	S	38.6	3.4	14.2	33.3	2.5	1.0	5.2	39.7	0.5	69.7	61.8	27.2	40.3	e
28	P	20.8	2.8	5.5	62.4	2.3	1.5	5.0	1.1	1.7	72.9	66.0	14.2	29.3	a
29	U	25.5	5.0	10.4	46.5	2.6	0.4	9.2	2.7	9.5	63.2	57.3	43.3	49.7	e
30	PL	8.6	1.1	3.6	53.3	21.7	1.1	11.7	0.9	28.3	45.4	39.8	13.1	28.0	e
31	P	21.2	2.8	5.7	63.3	2.3	1.5	2.5	0.8	1.8	79.1	70.2	19.0	34.1	a
32	PM	14.6	1.8	3.9	64.5	1.7	1.3	12.0	0.9	18.3	63.0	56.5	18.2	28.1	e
33	S	28.3	0.6	7.3	45.6	13.1	3.3	2.1	0.5	4.6	66.3	58.0	5.3	23.0	b
34	PL	12.8	1.4	3.4	66.6	3.2	1.1	11.3	0.2	32.8	57.2	50.4	40.3	45.3	d
35	PM	16.7	1.8	3.7	57.1	5.1	1.4	14.1	0.3	0.6	71.2	64.4	18.2	33.5	a
36	PM	14.1	2.3	5.1	57.1	1.4	0.2	19.6	0.1	0.8	65.1	56.5	4.3	16.2	c
37	HL	7.6	1.0	2.5	70.9	0.5	0.5	17.4	0.2	51.6	39.7	32.5	10.3	20.0	e
38	PM	16.9	1.5	5.4	36.5	26.2	0.7	12.4	8.9	9.0	86.3	76.3	11.3	27.2	b
39	U	23.7	2.2	6.0	59.0	5.1	1.7	1.7	5.6	0.7	62.2	55.5	16.4	24.0	d
40	P	21.1	2.8	5.4	62.4	2.3	1.3	4.5	1.4	2.7	73.0	65.0	13.1	32.2	a
41	P	21.8	2.4	5.7	64.4	1.3	1.7	2.4	0.2	0.7	78.3	67.5	12.0	27.1	a

[a] General nature:
P=Largely portland cement;
PL=Portland cement and hydrated lime mixtures;
PM=Portland cement mixed with unidentified material;
PN=Portland cement and natural cement mixtures;
N=Natural cement;
S=Large amounts of slag;
U=Not identified;
HL=Hydraulic or hydrated lime;

[b] Water repellent additions:
a=petroleum product
b=fatty acid derivative
c=rosin
d=unknown
e=not detected

2. FINENESS

The fineness (table 1)[1] was determined by wet screening with kerosene each cement through a no. 325 and a no. 450 sieve. The latter screen was made by chromium plating a no. 325 sieve until the openings were such that they would pass a particle less than 50 microns in diameter. The no. 325 sieve passes a 60-micron particle. The data indicate that with two exceptions the desirable fineness was realized.

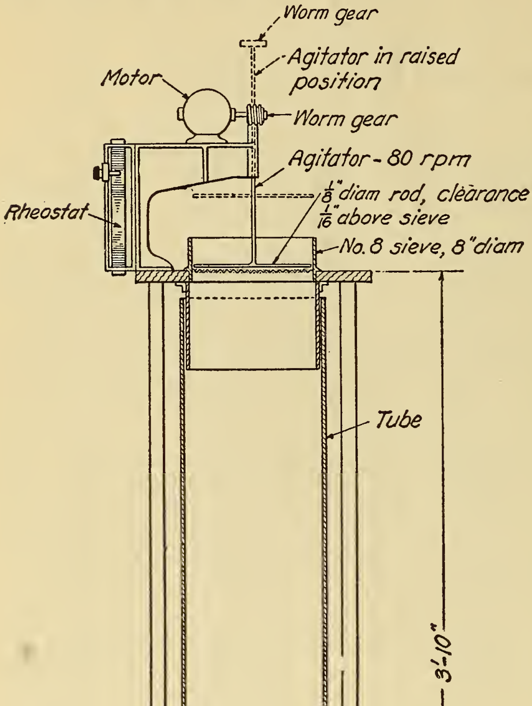

FIGURE 1.—*Apparatus for determining weight per unit volume of cement.*

3. WEIGHT PER UNIT VOLUME

The weight of each cement was determined as received, that is, without drying, sifting, or other preliminary preparation. The weight per volume of compacted cement was determined by rodding the cement with a ⅝-in. steel rod with a bullet-shaped end. The cement was rodded, in 3 layers, into a ⅓-cu. ft. aluminum measure. The excess cement was struck off with a straight edge. The weight per volume of loose cement was determined by use of the device shown in figure 1. The cement was shaken on a sieve, a small quantity at a time, with the agitator continually revolving, until the measure was heaping full. The excess was struck off with a straight edge. In either procedure, the measure was filled and weighed repeatedly until the results checked to the nearest 10 g. There was a decrease in weight per unit volume with succeeding determinations for the first 2 to 5 trials.

The rodded weight varied from 39.7 to 89.9 lb/cu ft (table 1), the mean being 64.7. The loose weight varied from 32.5 to 80.6 lb/cu ft, the mean being 56.3. Those cements that contained large propor-

[1] The supply of cements nos. 2 and 5 was exhausted prior to these measurements. Cement no. 6 was compounded in the laboratory. Sieve analysis of this cement would therefore not be comparable with the others.

tions of portland cement had the higher weights per cu ft. However, mixtures of portland cement with large proportions of hydrated lime were among those of lightest weight, e. g., cements nos. 5, 17, and 26.

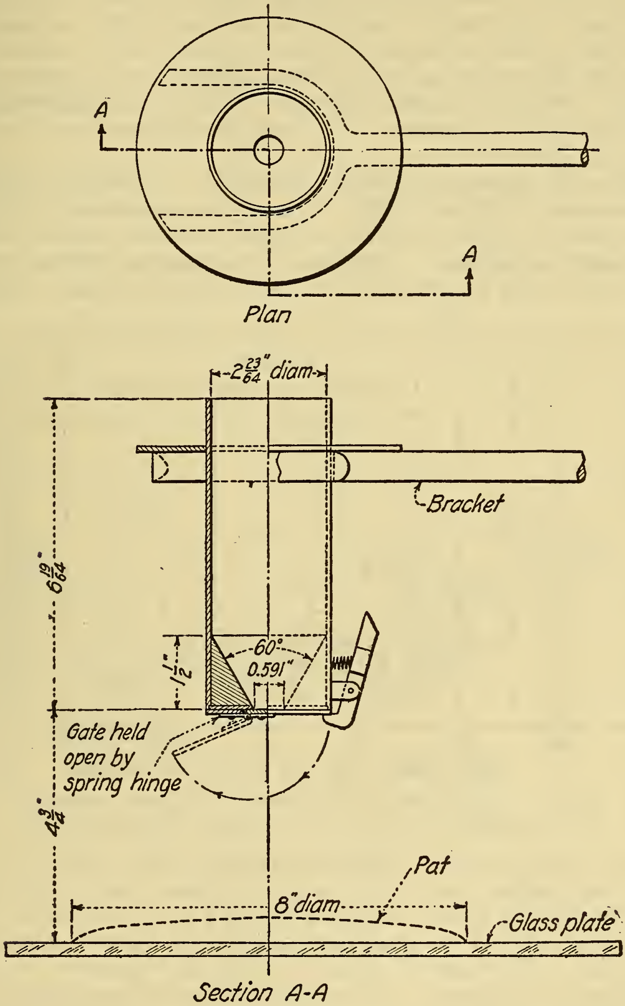

FIGURE 2.—*Device for determining volumetric flow of neat cement pastes.*

III. CEMENT-WATER PASTES

1. VOLUMETRIC FLOW AND SPREAD

The apparatus used to measure the volumetric flow and spread, shown in figure 2, was developed by committee C–1, cement, American Society for Testing Materials, for a study of a method to determine the normal consistency of portland-cement pastes.

The tests made with neat pastes (cement and water) included determination of the amounts of mixing water required to give a spread of 8 in., the time of flow of pastes and the bulk specific gravity of the pastes.

Cement and water were vigorously mixed for 5 min in a metal vessel with a metal stirrer. The container of the apparatus was then immediately filled level with the top. The time required for the paste to flow out of the container, from the time of springing the catch to the first break in the stream of paste, was measured with a stopwatch. The average of the measurements across several diameters of the paste as it had been allowed to flow onto the glass plate was termed the neat spread. Batches of different proportions of cement and water were tried until the spread was 8 in. within ±0.1 in.

The ratio of water to cement necessary to produce this spread ranged between 0.36 and 1.00. There was no consistent difference in water-cement ratios required for the cements with and without water-repellent additions. Further, no consistent relation was found between either the composition or the fineness of the cements and

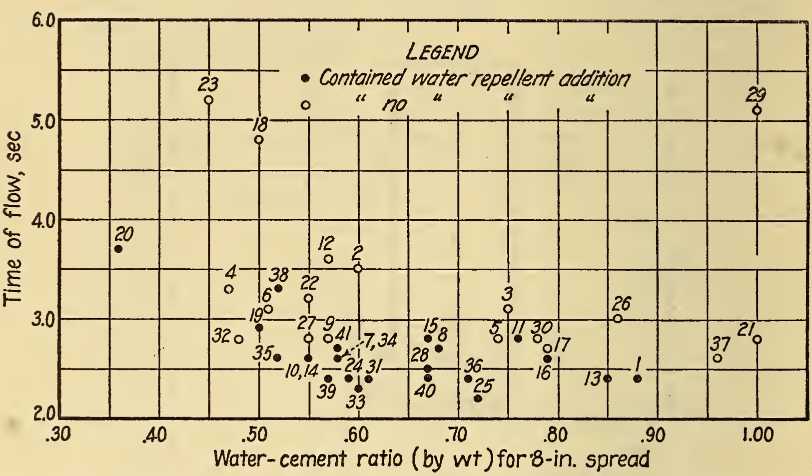

FIGURE 3.—*Relation between time of volumetric flow and water-cement ratio (by weight) of neat pastes giving an 8-inch spread.*

their water requirements. While the pastes made from the portland cements had rather low water-cement ratios, there were portland-cement blends with other materials which had equally low ratios.

The time of flow of the neat pastes from the container ranged from 2.2 to 5.2 sec. The time of flow of an equal volume of water from the container was 2.0 sec. The maximum deviation of any individual determination from the average of 3 was 0.2 sec. Figure 3 shows that generally the pastes made from cements containing water-repellent additions had a lesser time of flow.

2. BULK SPECIFIC GRAVITY

Neat pastes were prepared by mixing for 5 min cement with the amount of water required for an 8 in. spread. Immediately after mixing, the paste was poured into a 200 ml erlenmeyer flask with a top ground and fitted with a ground glass cover plate. The excess paste was struck off with the cover, and the outside of the flask wiped clean. The covered flask and contents were weighed to the nearest 0.1 g, and the bulk specific gravity of the paste was computed from the known volume of the flask and the net weight of the paste.

The bulk specific gravity of the neat pastes varied from 0.83 to 1.93 as shown in figure 4. The plotted points in this figure are in 2 groups. One contains 16 of the 23 cements which had water-repellent additions; the other, all the non-water-repellent cements and also the 7 cements not contained in the first group. The great differences in bulk specific gravities of the neat pastes were caused mainly by the retention of different amounts of air incorporated during the mixing. The various proportions and specific gravities of the component materials were also factors of moment. It was evident that during the mixing of the pastes those containing water-repellent additions readily incorporated air. No direct determination of the amounts of air present in each case was made. An indication of the air incorporated was obtained from the total volumes of dry rodded cement plus water used to produce 1 volume of the neat paste. The computed sum of the entering materials varied from 0.83 to 2.00 times the actual volume of paste produced and was less than 1.00 for 10 of the cements, which proved that these pastes contained air. The water-cement ratio of the neat pastes is shown in the last column of table 2.

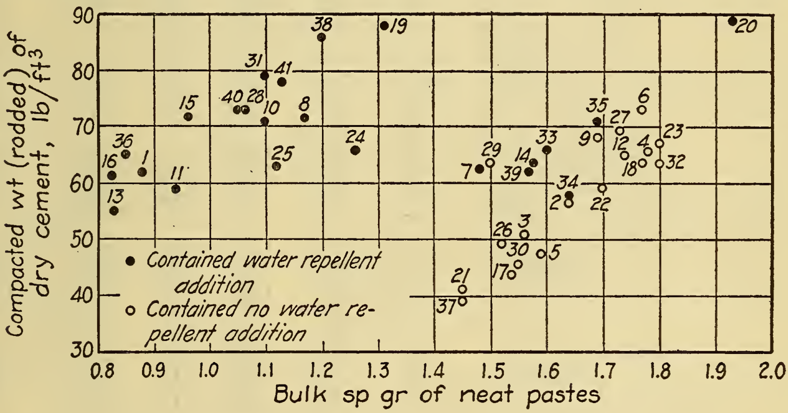

FIGURE 4.—*Relation between weight per cubic foot of cement (compacted) and bulk specific gravity of neat pastes.*

IV. MORTARS

1. FRESH MORTAR

The compositions of the mortars were as follows:

Mortar X.—One part of cement, 3 parts of standard Ottawa sand, by weight. In the stirring resistance tests and in the measurements of the water-retaining capacity, the amount of water was varied by increments of 1 percent of the weight of the dry materials. For the measurement of length change and for determining the compressive strength, 3 different amounts of water were used, namely, that to produce normal flow,[2] 1 percent more and 1 percent less. The amount of water required for normal flow was used in preparing specimens for the measurements of transverse strength, absorption, durability, and for the study of efflorescence.

[2] Normal flow is a flow of 100 to 115 obtained upon a 10-in. flow table using 25 one-half in. drops. See Federal specification SS-C-181 for masonry cements, or Proc. ASTM. 32, pt. I, 698 (1932).

TABLE 2.—*Composition of mortars*

Cement number	Water-cement and cement-sand ratios					
	Water-cement ratio by weight at normal flow			Cement-sand ratio by weight		Water-cement ratio by weight in paste, mortar Z
	Mortar X	Mortar X–1	Mortar Y	Mortar Y	Mortar Z	
1	[a] 0.72	[b] 0.68	[c] 0.90	[c] 1:5.2	[c] 1:5.8	0.88
2	.68	.64	--------	--------	1:2.6	.60
3	.72	.68	1.20	1:6.4	1:3.1	.75
4	.60	.52	.77	1:4.9	1:2.3	.47
5	.76	.72	1.20	1:6.8	1:3.0	.74
6	.64	.64	.79	1:4.4	1:2.3	.51
7	.64	.60	.72	1:5.1	1:2.9	.58
8	.64	.64	.81	1:4.5	1:3.9	.68
9	.72	.68	.86	1:4.8	1:2.5	.57
10	.54	.52	.64	1:4.6	1:4.0	.55
11	.68	.68	.80	1:5.5	1:5.1	.76
12	.64	.60	.91	1:5.1	1:2.5	.57
13	.68	.68	.85	1:5.8	1:6.1	.85
14	.56	.56	.80	1:5.1	1:2.7	.55
15	.60	.56	.78	1:4.5	1:4.7	.67
16	.56	.54	.75	1:5.3	1:4.4	.79
17	.76	.76	1.49	1:7.5	1:3.2	.79
18	.56	.56	.80	1:5.0	1:2.3	.50
19	.54	.48	.60	1:3.7	1:3.1	.50
20	.54	.52	.59	1:3.6	1:1.9	36
21	.88	.88	1.50	1:7.7	1:3.8	1.00
22	.64	.60	.95	1:5.5	1:3.5	.55
23	.56	.54	.77	1:4.8	1:2.2	.45
24	.56	.56	.66	1:5.0	1:3.4	.59
25	.60	.60	.78	1:5.1	1:4.2	.72
26	.80	.80	1.37	1:6.5	1:3.3	.86
27	.68	.64	.85	1:4.6	1:2.4	.55
28	.56	.52	.66	1:4.4	1:4.3	.67
29	1.04	1.00	1.33	1:5.1	1:3.6	1.00
30	.76	.70	1.29	1:7.1	1:3.1	.78
31	.52	.52	.60	1:4.1	1:4.0	.61
32	.60	.56	.89	1:5.1	1:2.2	.48
33	.56	.50	.68	1:4.9	1:2.7	.60
34	.68	.64	1.06	1:5.7	1:2.6	.58
35	.56	.56	.70	1:4.5	1:2.5	.52
36	.56	.50	.63	1:5.0	1:5.5	.71
37	.76	.76	1.52	1:8.2	1:3.6	.96
38	.48	.48	.52	1:3.7	1:3.5	.52
39	.56	.56	.73	1:5.2	1:2.7	.57
40	.56	.52	.65	1:4.4	1:4.3	.67
41	.52	.52	.58	1:4.1	1:3.8	.58

[a] Mortar X=1:3, by weight cement, standard sand mortar.
[b] Mortar X–1=1:3 by volume cement mixed sand mortar (see text).
[c] Mixed sand used in mortars Y and Z.

Mortar X–1.—One part of cement, 3 parts of mixed sand, by weight. The mixed sand was composed of 2 parts by weight standard Ottawa sand and 1 part pit-run Ottawa sand. The fineness modulus was 2.62. Three different amounts of water were used, namely, that which produced normal flow, 1 percent more, and 1 percent less. This mortar was used in compressive tests only.

Mortar Y.—One part of cement and 3 parts of the above-described mixed sand by dry-rodded volumes. Enough water was added to this mortar to produce normal flow. The proportions of sand, cement, and water by weight are given in table 2. This mortar was studied with all the tests except linear changes during hardening.

Mortar Z.—One volume neat cement paste to 1.57 volumes of the dry-rodded mixed sand,[3] the water content of the paste being that required to give a spread of 8 in. plus or minus 0.1 in. in the neat spread test. The proportions by weight are given in table 2. Mortar Z was tested for strength in compression only.

(a) PREPARATION OF MORTARS

For mortars X, X–1, and Y, the sand and cement were mixed to a uniform color in a metallic vessel. Water was then added and the

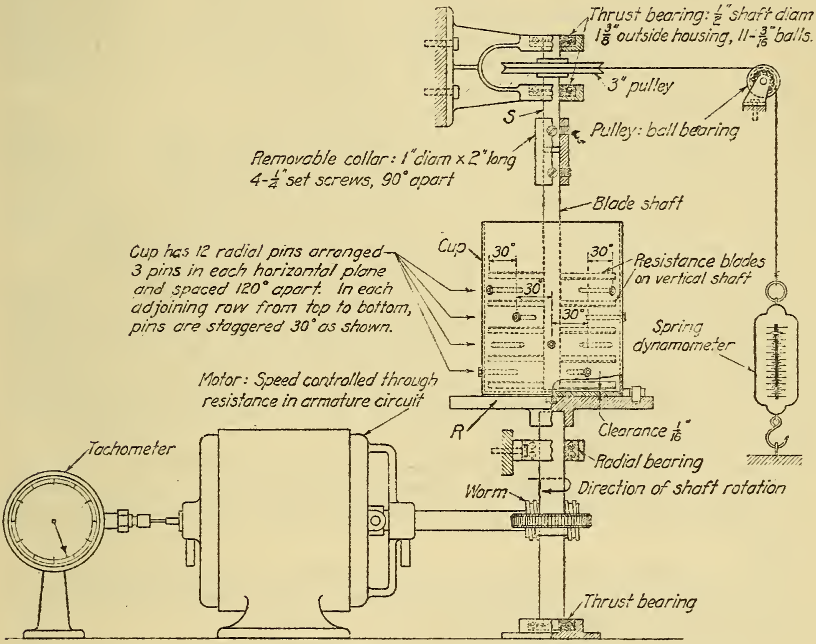

FIGURE 5.—*Device for measuring resistance of mortars to stirring.*

mixing continued for 5 min. The mortars were then allowed to stand for 14½ min., when they were again stirred for one-half min. This procedure was followed in order to incorporate the ingredients into a homogeneous mass, for in some, segregation resulted on standing. For mortar Z the paste was weighed into the metallic vessel and the weight equivalent of 1.57 volumes of mixed sand added and the mixing continued for 5 min. It was allowed to stand for 14½ min, and again mixed for one-half min. Many of the cements, particularly those containing integral water-repellent agents or plasticizers, showed a marked resistance to wetting, particularly during the first 2 or 3 min. Fourteen and one-half min was assumed adequate as a soaking period.

(b) STIRRING RESISTANCE AND FLOW

The device shown in figure 5 was used to determine the relative "workability" (stirring resistance) of the mortars. As the apparatus

[3] Usually mortars are proportioned by fixing the ratio of cementing material to sand, the consistency being controlled by the amount of water added. In contrast to this, mortar Z was proportioned by fixing the ratio of the volume of the pastes to the volume of the sand. Preliminary tests indicated that the mortars with few exceptions would have the desired normal flow of 100 to 115 percent when this ratio was 1:1.57.

was first constructed there were no projections attached to the inside of the cup. Observations showed that the mortar slipped on the interior surfaces of the cup, indicating that the resistance was a measure largely of the friction of the mortar on metal. This was particularly noticeable in the stiffer mixes. As it seemed that the working properties of mortars are more a function of resistance to deformation than of resistance to sliding on a metal surface, the apparatus was changed to its present form. Although the blades and projections caused the mortars to deform when the cup was rotated, there may yet have been some slippage at the metal-mortar interface. In this device a revolving cup contained the mortar, in which were inserted several horizontal blades on a shaft connected with a spring balance to measure the resistance developed.

In this part of the investigation mortars X and Y were used. The amount of water in mortar X was varied from that which was found to produce a resistance of about 1,200 g to that which resulted in about 200 g by increments of 1 percent of the weight of the dry material. If less water were used some of the mortars formed balls and gave erratic results; if more, there was distinct segregation.

A great many preliminary tests were made with the present device in which the resistance was measured over a wide range of speeds. Mortars, neat pastes, dry sand, fine lead shot, and a few enamel slips were used in these tests. For all these, the resistance at low speeds decreased rapidly as the speed of rotation increased from one-half to about 5 rpm; for higher speeds from 20 up to 70 rpm, the resistance increased moderately.

The procedure in making the observations was as follows:

1. A mortar batch weighing 1,350 g was used in all cases. Owing to the different densities of the mortars, the volumes varied considerably.

2. The mortar was placed in the cup and the blades inserted.

3. The cup was placed on the rotating platen (R) and the blade shaft connected to the shaft (S).

4. The cup was then rotated at 25 rpm for 5 min.

(a) The load on the balance was then noted at the end of the 5-min. period.

(b) The speed was next increased to 50 rpm. The load was then noted after 1 min. at this speed.

(c) The speed was then further increased to 70 rpm and the load again noted at the end of 1 min at this speed.

The measurements indicated in 4 (a), (b), and (c) were repeated, and then again repeated with the exception that 4 (a) was read at the end of 1 min instead of 5 min for the second and third set of readings.

The three speeds at which the observations were made were used as the result of preliminary tests. These tests indicated that a constant resistance could not be produced under a given set of conditions, at the very low speeds, within a reasonably short time. But it was found on studying the data that for a mortar made of any of the cements, the effect of speed on resistance for any one water-cement ratio between high and low speeds was not as great as the preliminary work indicated. Thus, the average difference for mortar X for all cements for the maximum amount of water used with each cement between the high and low speeds was 60 g. The difference, when

the minimum amount of water was used, was 100 g. Such values are but little beyond the experimental error. Hence the data give the average resistance for the three sets of readings.

The data do not show to what extent stirring resistance was a function of the deformation resistance of the mortars. The observations indicate, however, that surface resistance of the mortar on metal may have contributed a part. With the speeds used, turbulence was observed on the free surface of the mortar which would indicate the same condition within the mortar mass; hence it would be expected that the resistance values were influenced somewhat by the density of the mortars. Nevertheless, the resistance seemed to provide a numerical measure which agreed with the judgment and experience of the operator as to the working properties.

The difference between the amount of water used in the mortars, which resulted in a resistance of 200 g, and that which gave 1,200 g has been termed the "water range of the mortars." This is represented graphically by the lengths of the bars in figure 6. Their lengths and positions in the graph are equally important. A long, bar indicates that the resistance is not as sensitive to changes in the water content as that represented by a short bar. A bar toward the left of the figure indicates that the mortar required less water to produce a workable mix than one to the right. It was observed, while preparing the mortars, that those containing cements having water-repellent additions generally worked more easily than those prepared from the non-water-repellent cements. The added material appeared to act as a plasticizing agent. It can be noted in figure 6 that those mortars which contain water-repellent cement are more to the left of the figure than those without the additions. To produce equal ease of working—resistance values within the same range—in the non-water-repellent mortars it was necessary to use more water.

Figure 7 shows the relation between resistance and water content of a few of the mortars of type X. Graphs representing data for the other mortars of this type would be between the extremes shown here. It was found that the logarithm of the resistance was proportional to both the percentages of mixing water and the percentage spread of the mortar as measured by the flow table. Use was made of these relations in extrapolating values of percentage flow and percentage of mixing water, as shown in figure 6.

Two important facts are demonstrated by these curves: first, that to obtain the same resistance values for different cements in this type mortar, the water requirements varied over a wide range; second, that the resistance values of the mortars of some of the cements change more rapidly than others with equal changes in the mixing water. For example, normal flow of the mortar made from cement 20 gave a resistance of approximately 1,520 g, while with a mortar from cement 1, it gave a resistance of about 350 g. Mortars of the Y type (1:3 mixed sand by volume) showed similar relations. Thus, the mortar from one cement of normal flow gave a resistance of 500 g, whereas the mortar from another cement gave a value of 2,350 g. Apparently, cements which produce "fat" mortars will have lower resistance values at normal flow than those which yield harsh mortars.

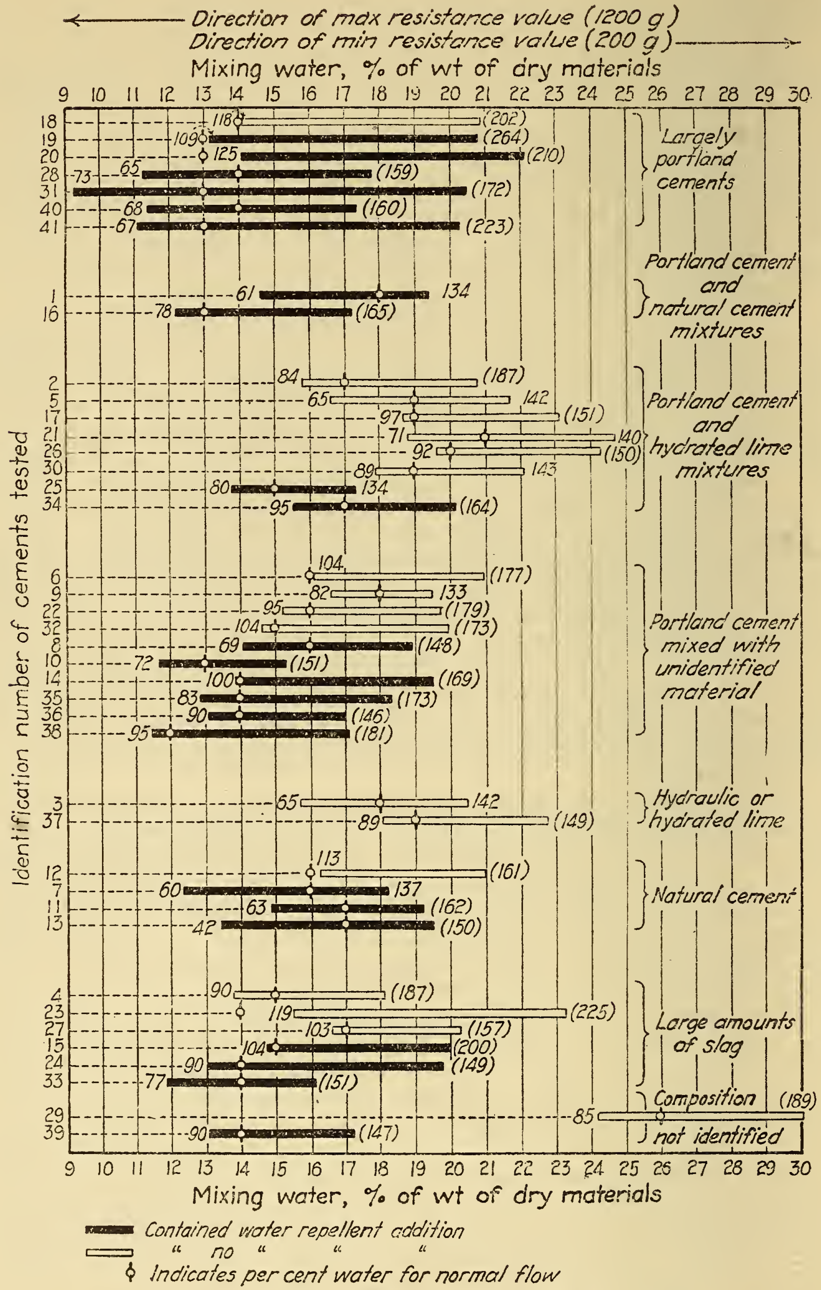

FIGURE 6.—*Water range of cements in type X mortars.*

Extreme resistance values plotted are 200 and 1,200 g. The percent water corresponding to these was obtained by interpolation and extrapolation from graphs plotted from original data.

The numbers at the ends of the bars are percentage increases in spread as measured on the flow table at the corresponding amounts of water; those in parentheses are extrapolated values.

Changes in the flow of mortar X throughout all water-cement ratios found before and after the stirring resistance tests served to classify the cements into three groups. Group 1, in which the final flow was greater than the initial flow, included cements nos. 3, 5, 13, 16, 21, 28, 31, 33, 35, 36, 40, and 41. Group 2, in which the final flow was less than the initial flow, included cements nos. 1, 2, 6, 8, 9, 10, 11, 12, 14, 15, 17, 19, 20, 22, 23, 25, 26, 27, 32, 34, and 37. Group 3, in the low range of water-cement ratios, cements nos. 4, 7, 18, 24, 30, 38, and 39, produced greater initial flow than the final; while with the higher water-cement ratios the initial flow was less

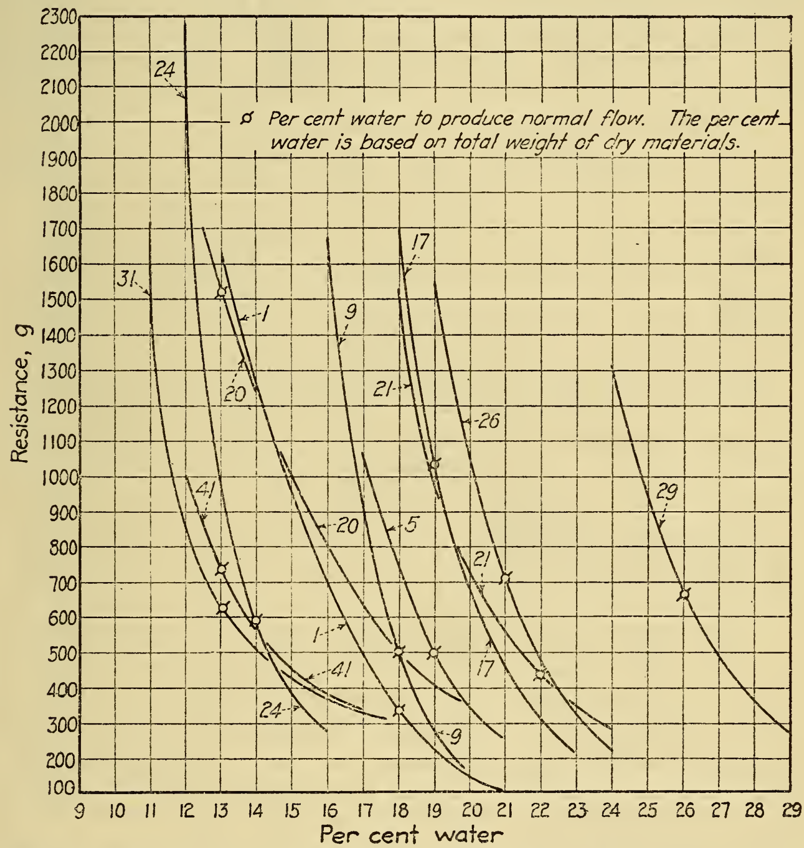

Figure 7.—*Variation of stirring resistance with changes in water content, mortar* X.

than the final flow. The converse of this was noted with cement no. 29.

It was observed that group 1 includes cements having water-repellent additions or large proportions of lime. Those in group 2, if containing water-repellent materials, were relatively coarse.

Approximately 16 min had elapsed between the making of the 2 observations, during which time hydration of the cements may have progressed considerably. The hydration would usually be considered as producing a stiffening and therefore reduced flow. But it is conceivable that the early hydration products might be such that

they would confer unctuousness and therefore greater flow to a mortar. It is consequently not surprising that certain of the mortars have developed greater flow during agitation and the lapse of the time required for making the resistance observations.

How the several cements affected the relative resistance of mortar X (1:3 by weight standard sand) and of mortar Y (1:3 by volume mixed sand) is shown in figure 8. Here it is seen that with the exception of the mortars made from cements nos. 19 and 20, the resistance of mortar Y is considerably higher than that of mortar X. The reason for increased resistance is readily seen to be due to the greater proportion of sand present in mortar Y (table 2) and, therefore, the less amount of the cement-water paste which furnishes the plasticizing or "work-reducing" agent in the mortar. Mortars made from cements nos. 6 and 9 contained a high percentage of portland cement

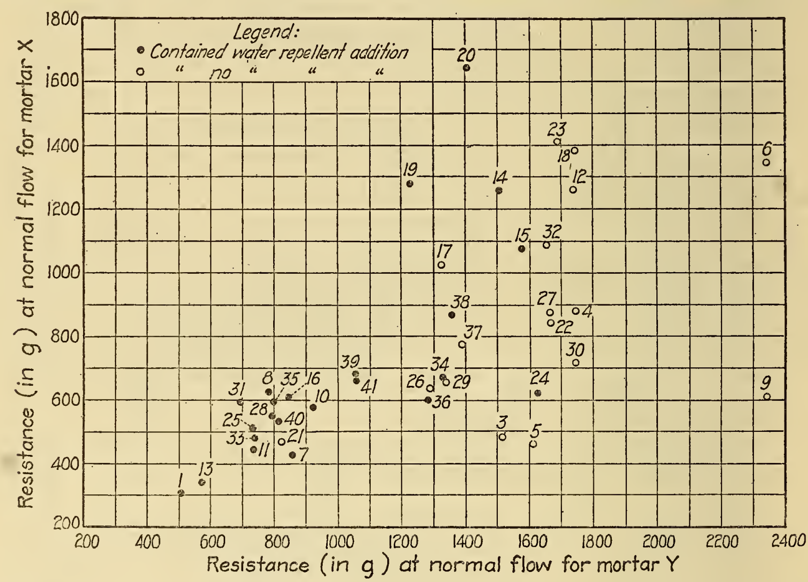

Figure 8.—*Relation between stirring resistance of mortars X and Y at normal flow.*

with very poor plasticizing additions. From a comparison of figures 9 and 10, it will be seen that insofar as the water requirements at normal flow are concerned, mortar Y, made of a graded sand containing considerable fines, required more water than mortar X, composed of 1 size of relatively large sand particles. Cements nos. 3, 5, 17, 21, 26, 29, 30, and 37, which were high in hydrated lime, required more water for the same workability than other cementing materials, and caused the mortar containing them to have high water requirements.

In figures 9 and 10 there have been plotted the resistance values and water-cement ratios of mortars X and Y at normal flow. The mortars have been studied at this consistency largely because of the inclination to accept the normal flow as giving a consistency closely approaching that which would be used in the practical application of the mortars. This inclination is evidenced by the inclusion of the normal flow as a measure of the consistency in both the Federal [4]

[4] Normal flow is a flow of 100 to 115 obtained upon a 10-in. flow table using 25 one-half in. drops. See Federal specification SS–C–181 for masonry cements, or Proc. ASTM 32, pt. I, 698 (1932).

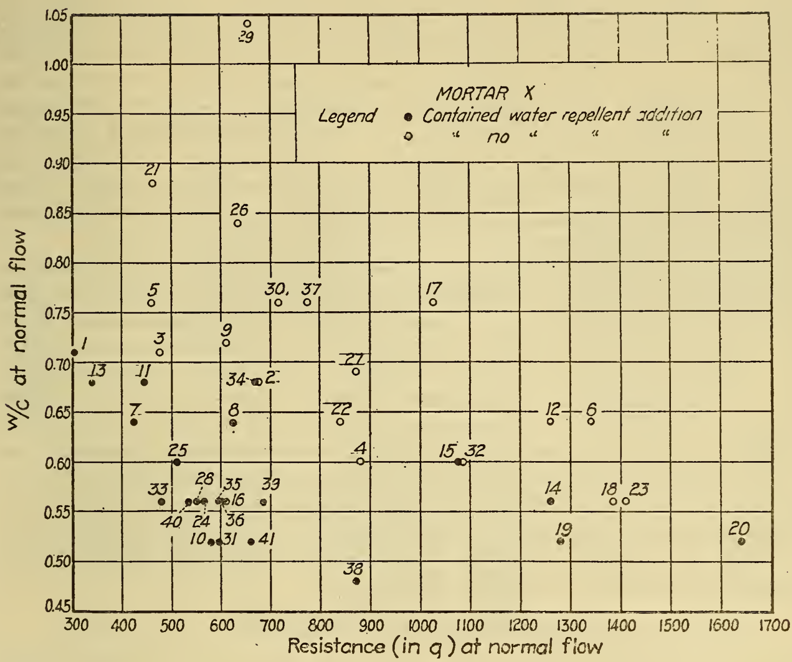

FIGURE 9.—*Relation between water-cement ratio and stirring resistance of mortar X at normal flow.*

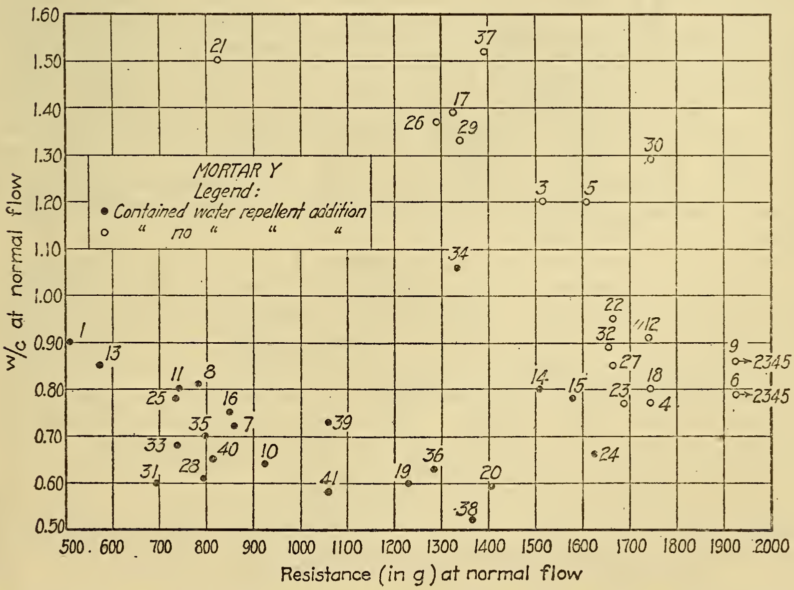

FIGURE 10.—*Relation between water-cement ratio and stirring resistance of mortar Y at normal flow.*

and the ASTM standards for masonry cement. A comparison of figures 3, 9, and 10 leads to the conclusion that the much simpler neat spread tests bring out the differences between the cements as readily as do the more involved stirring-resistance measurements. There is no doubt that those mortars in figure 9 having a resistance less than 800 g would be classified as very workable, and those in figure 10 less than 1,400 g would be similarly classed. Most of the mortars of type Y, having a resistance of more than 1,400 g, were made from those cements which had a time of flow in the neat spread test of more than 2.6 sec.

Attention has previously been called to the relatively high water-cement ratios required by cements nos, 3, 5, 17, 21, 26, 29, 30, and 37. Their high percentage of hydrated lime demanded these high ratios to obtain normal flow. In figure 9 it is noted that these high ratios are accompanied by relatively low resistance values, while in figure 10 the resistances of mortar of the Y type made from these cements are high. But it has previously been brought out that the low unit weights of these cements resulted in mortars proportioned on a 1:3 volume basis having very low cement contents. Hence, there can be seen the effect of the large amount of hydrated lime on this property of resistance here studied as a measure of workability. As a class the portland cements are about equally divided between the easily and poorly workable mortars.

(c) WATER RETAINING CAPACITY

Mortars X and Y were used in the tests for water-retaining capacity with the same quantity of water as used in determining the resistance values.

A perforated porcelain dish, containing a weighed quantity of the mortar on a sheet of hard filter paper, was placed over a device which could be evacuated to a carefully controlled degree for certain desired periods.[5] A vacuum of 2 in. of mercury was produced by an ordinary water aspirator and controlled by a mercury-column relief valve. Such a vacuum was found to remove approximately the same amount of water in 1 to 3 min as a dry process brick having an absorption of about 6.5 percent in 3 min. A preliminary study of the water removed from mortars by such brick furnished this information.

The mortars were exposed to the action of the reduced pressure for 1 and 3 min. Freshly prepared samples were used for each exposure; duplicate tests were made and each was preceded and followed by a flow measurement on the mortar. In many instances, all the removable moisture was extracted before the end of the 3-min exposure, so that the mortar crumbled in the flow test, consequently there are no flow data for the 3-min period. The water remaining in the mortar after the evacuation was determined by the residual weight.

The data are presented in figures 11 and 12. The first of these figures shows the ratios for the mortars of the X type made of all of the cements when the water content corresponded to that resulting in maximum and minimum stirring resistance. As would be expected, there is more water removed by the 3-min suction than by the 1, but the ratio between these 2 periods is not constant for all of the mortars.

[5] This device, although developed by one of the authors of this paper, was also used by Palmer and Parsons, and is described in their paper, *Rate of stiffening of mortars on a porous base*, Rock Products, **35**, no. 18 (1932).

While generally those cements having a large percentage of material passing the no. 450 sieve showed better water retention than the coarser cements, this did not always follow. Cement 29, the coarsest

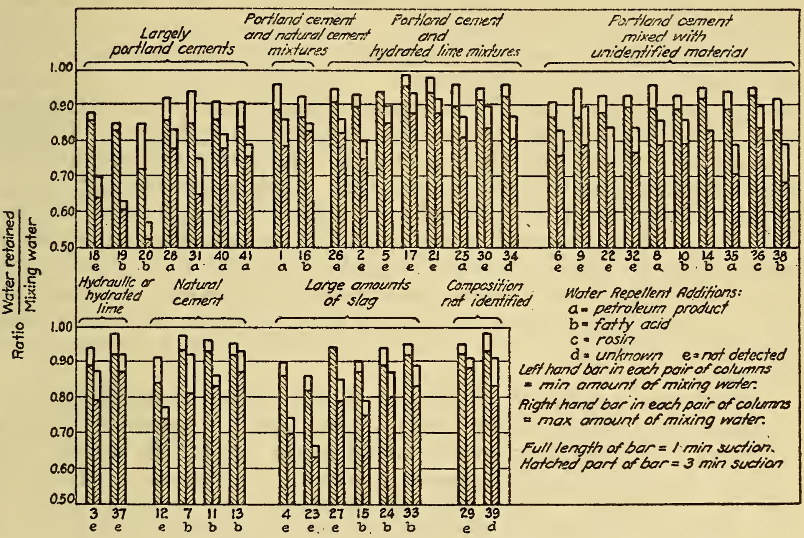

FIGURE 11.—*Water-retaining capacity of cements in type X mortar.*

ground cement, had very excellent water retention. Composition seemed to be a dominant feature in controlling this property. Natural cements or cements containing much hydrated lime or partially

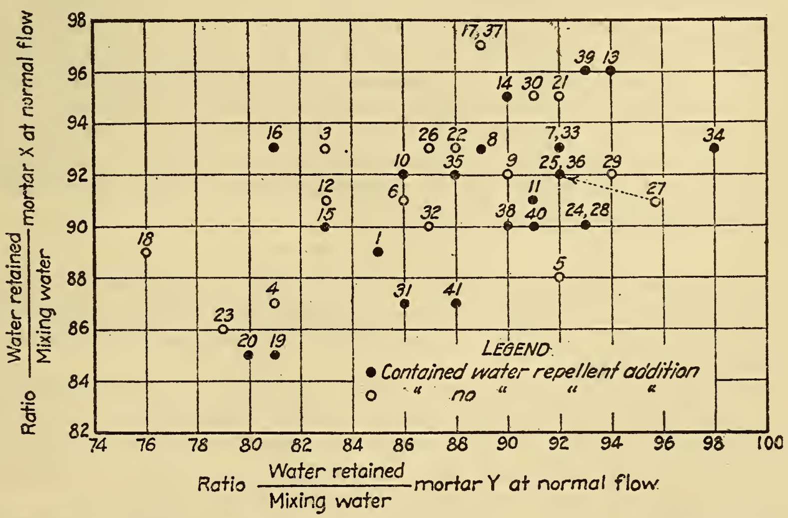

FIGURE 12.—*Relation between ratios of water retained at the end of one-minute suction to mixing water of mortars X and Y at normal flow.*

hydrated additions had high water retention. It is not possible to say if these materials are effective only because of their extreme fineness of grind or to their nature being such as to hold tenaciously large

amounts of water. The presence of a water-repellent addition was apparently not effective in reducing the withdrawal of the water.

The relation between the water-retaining properties of mortar X and mortar Y when the percentages of water used corresponded to normal flow is shown in figure 12. More than half of the mortars of the X type retained water to a greater extent than mortars of the Y type made from the same cement. If the size gradation of the sands used is considered, it would be expected that the Y type containing the finer sizes would retain the water to the greater degree. But again it must be remembered that mortar X is made on the weight basis of proportioning and, therefore, contains much more cement than the other, proportioned on the volume basis. The apparent reason for the exceptions just noted seems to be that those cements which were either coarsely ground or had a high bulk weight, gave poorly graded mortars of type X and hence did not have high water-retaining properties in comparison with mortars of the Y type in which the particle sizes were better graded and which contained the lesser amounts of cement.

There was a marked difference in the rates of stiffening of the mortars when subjected to 1 min. of suction. A measure of this was obtained by comparing the amount of water lost by the mortar after 1 min. with the estimated increase in stirring resistance which attended this loss of water. The stirring resistance of mortars made with cements nos. 7, 13, 17, 21, 36, and 39 increased less than 200 g when the water content was changed from that required for a resistance of 200 g to that remaining in the mortar after 1 min. suction, whereas the increase for mortars of cements nos. 4, 12, 18, 19, 20, and 23 was more than 900 g. Those of the first group would tend to retain their workability when used in contact with masonry units of rapid absorption while those of the latter group would tend to stiffen rapidly. The results of the sieve analyses of the cements (table 1) show that the fineness of the cement as indicated by the percentage retained on the no. 450 sieve was one of the factors affecting the rate of stiffening of the mortars. Of the cements having low rates of stiffening, all had 24 percent or less retained on the no. 450 sieve except no. 17, which had 28.2 percent, whereas of those showing a high rate of stiffening all except no. 19 had more than 31 percent retained on the no. 450 sieve, this exception having 25.4 percent.

(d) VOLUME YIELD

The volume yield of mortars Y and Z was determined by weighing the same volume of mortar in all cases and calculating the total volume yield per rodded volume of cement from the weights of the materials entering the batch.

These data were also of assistance in making an approximation of the amount of air in the mortar. Thus, the volume of air (V_a) incorporated during mixing would be equal to $V_m-(V_s+V_c+V_w)$ where V_m is the volume of the mortar, and V_s, V_c, and V_w the absolute volumes of sand, cement, and water, respectively.

The yield of mortars of the two types from the various cements is presented in figures 13 and 14. The former also gives the calculated percentage of air by gross volume of the mixture. One volume of cement plus 3 volumes of sand and enough water to give normal flow resulted in yields varying from 3.29 to 4.19. It is clearly seen, however, how much the yields are influenced by the presence of air.

Further, as previously stated, the presence of the water-repellent compounds induced the incorporation of the air during the mixing,

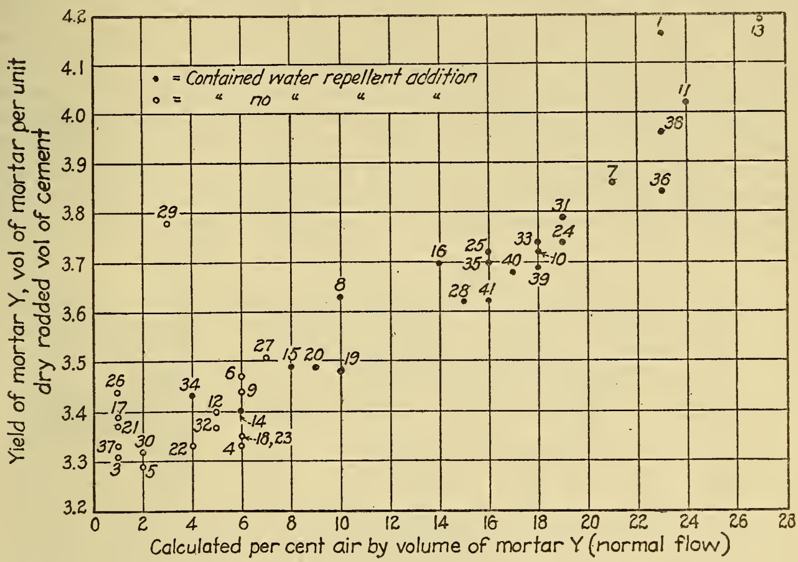

FIGURE 13.—*Relation of volume yield to amount of air present in mortar* Y *at normal flow.*

and hence, with two exceptions, those cements containing such additions gave mortars of high air content and high yield. Why two cements

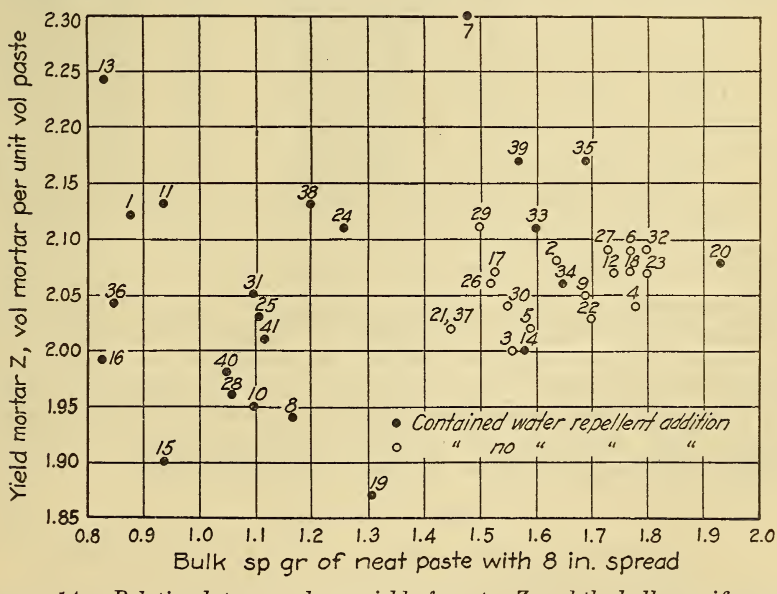

FIGURE 14.—*Relation between volume yield of mortar* Z *and the bulk specific gravity of the neat pastes.*

(nos. 14 and 34) are exceptions is not clear, although no. 34 contained such a small amount of the addition that it could not be identified.

Figure 14, in addition to giving data showing the yield of mortar Z, again presents the data showing the bulk specific gravities of the corresponding pastes when the amount of water used gave an 8-in. spread. Again, the grouping of the results depends upon whether the mortar contained water-repellent additions or not. Those containing such additions generally had low specific gravities because of occluded air, while the cements without water-repellent material are closely grouped with a much higher average bulk specific gravity. Otherwise the graph shows that there is but a slight relation between bulk specific gravity of cement pastes and yield of mortars. One explanation of this is the effect of the sand in mixing the mortars in

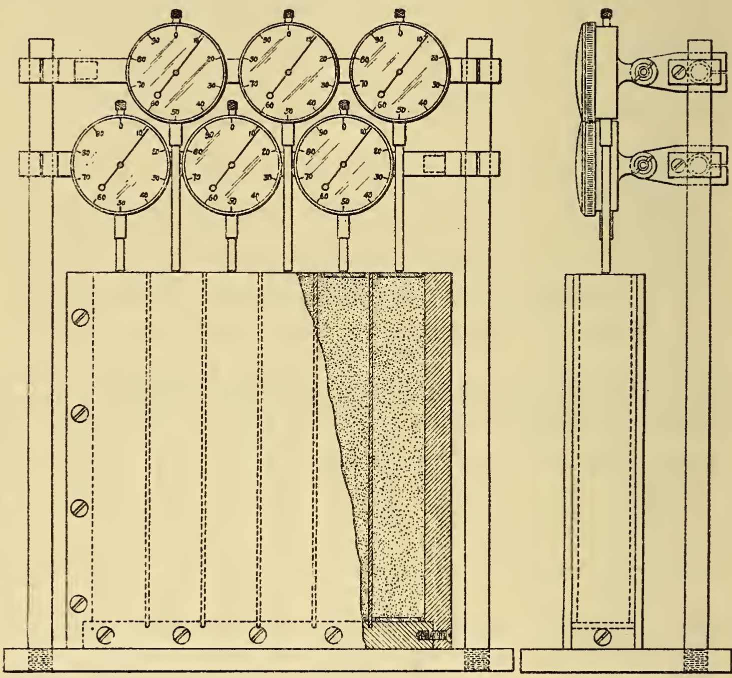

FIGURE 15.—*Device for measuring length change of specimens during hardening.*

either breaking down the paste-air emulsions or tending to cause more occlusion of air. This was particularly evident in the case of the cements containing water-repellents. In mixing such mortars it was evident to the operator that additional air was being incorporated into some, and the air-paste emulsions were being broken down in others. This may account for the wide distribution of yield of mortars made from pastes of the same specific gravity.

2. SET MORTAR

(d) LINEAR CHANGES DURING AND AFTER HARDENING

Specimens for one series of tests with mortar X were made with three different proportions of water, viz, that which produced a mortar having normal flow, that with 1 percent more, and that with 1 percent

less. The specimens were cast and measured during their hardening period in the apparatus shown in figure 15. The collapsible mold used was divided into six compartments, each 1 by 1 by 8 in. Each compartment was lined with waxed paper, and before filling with the mortar, a glass plate seven-eighths in. square was placed in the bottom. The mortar was gently rodded into each compartment and after filling, a small glass plate, similar to the one at the bottom, was placed upon the top. The mold was then set underneath the dial micrometers and the changes in length measured to 0.005 percent. The gages were so placed that their stems rested upon the centers of the top glass plates. They were read immediately and then hourly for the first 7 hours. When the specimens were sufficiently strong, usually at the end of 30 hours, they were removed from the mold and placed in a damp closet for 1 week, then in water storage for 1 week, after which one half were stored in air and the other half remained in the water. The changes in length during the damp closet storage were measured at the end of 3 days and 7 days, and later at the end of each week for the first 4 weeks, and thereafter at the end of each month.

Part of the data for the specimens gaged to normal flow are shown in table 3 in condensed form; these values were generally nearer those obtained with the higher than with the lower percentage of water.

The contraction noted while the specimens were in the molds was a resultant of the compacting of the mortars while in the plastic state, owing partly to the action of gravity, to the change accompanying the chemical reaction of the cement and water, and also possibly to the loss of air. The mortars made from cements having water-repellent additions shrank 0.043 percent more than those without, probably because of the greater amount of air incorporated. In a number of cases the changes during this period were very marked.

The linear changes in storage of high humidity subsequent to the setting were found to be of minor degree, possibly because of the heterogeneous nature of the cements—mostly mixtures of several types of cement, and lime, silica, etc. No data were available or obtainable on how individual cements in the mixtures deport themselves, but no doubt it would be possible to compound some mixtures so that the contraction of one constituent might counteract the expansion of another. Subsequent to setting, there was no marked difference in the linear change of the water-repelling and nonwater-repelling mortars. Hence, the addition of such agents cannot be considered as having contributed to the surprisingly small changes noted.

In the majority of cases, however, the shrinkage after hardening and during a year in the air was large. The data also show that a number of mortars having a large shrinkage in air have a relatively small increase in length when stored in water. Apparently the net change in length is the resultant of the shrinkage inherent in the hardening of the cement, regardless of the nature of the storage and the expansion expected in storage in water.

Table 3 also gives data showing linear changes of 1 by 4 by 12 in. bars which were subjected to alternate cycles of wetting and drying for 1 yr, and then broken transversely to obtain the moduli of rupture (fig. 18). Generally, these bars after 1 wk in the damp closet at 21° C were sufficiently strong to permit their being removed from the molds;

if not, they were allowed to remain until they could be more safely handled. After the first drying of 1 wk at 65° C they were placed in water for 1 wk at 21° C. This cycle was repeated until the end of the 38th wk. Then after drying for 1 wk, they were allowed to remain in water for 2 wk, dried for 1 wk, and then placed in water for 7 wk. The specimens were measured at the end of each period of storage. In the fifth and sixth columns of table 3 are given the shrinkages during the first and last periods of drying, respectively. In the seventh column the differences in length between the first and last dryings are shown.

TABLE 3.—*Percentage length changes of bars of mortar* X

[Blank spaces indicate the bars broke during handling before the measurements could be made]

1	2	3	4	5	6	7
	Bars 1 by 1 by 8 inches			Bars 1 by 4 by 12 inches		
Cement number	Shrinkage during first 24 hours	Length increase during 1 year in water	Shrinkage during 1 year in air	Shrinkage during first drying on removal from damp closet	Shrinkage during last drying at about 1 year	Change in length between first drying at about 1 week and last drying at about 1 year
1	0.256	0.040		0.154		
2	.307	.012	0.115			
3	.496	.038	.126	.068	0.038	+0.033
4	.087	.004		.040		
5	.499	.085	.070			
6	.196	.011	.120	.087	.046	+.010
7	.440	.057	.137	.102		
8	.585	.020	.164	.128	.034	+.016
9	.375	.013	.133	.091	.029	−.015
10	.384	.017	.068	.063	.036	−.032
11	.510	.090	.111	.026	.061	+.052
12	.484	.021	.109	.078	.077	−.012
13	.332	.121	.112	.124		
14	.218	.013	.065	.080	.032	+.021
15	.337	.011	.090	.071	.038	−.055
16	.340	.004	.122	.101	.032	−.065
17	.194	.051	.073	.075	.052	+.093
18	.216	.013	.055	.040	.027	−.006
19	.191	.016	.085	.074	.034	+.019
20	.131	.029	.069	.066	.039	+.057
21	.294	.027		.058	.010	+.022
22	.502	.053	.086	.059	.040	+.112
23	.166	.024		.043		
24	.406	.039	.090	.131		
25	.377	.030	.081	.067	.033	+.041
26	.268	.148	.052	.080		
27	.463	.016		.083	.019	+.031
28	.198	.019	.113	.092	.032	−.011
29	.216					
30				.069	.022	+.008
31	.345	.019	.195	.087	.042	−.023
32	.174	.009	.076	.069	.035	+.012
33	.220	.050		.036	.032	−.020
34	.255	.013	.103	.082	.032	+.019
35	.278	.009	.080	.072	.039	+.005
36	.309	.009	.096	.067	.028	−.027
37	.331	−.001	.116	.055	.023	+.007
38	.505	.025	.082	.088	.039	+.029
39	.530	.086	.070	.069		
40	.482	.014	.106	.089	.037	+.021
41	.494	.016	.101	.093	.037	+.006
Average	.335	.033	.099	.078	.036	+.012

A comparison of columns 4 and 5 shows that 1 wk's drying at 65° C, after about 1 wk's aging in the damp closet, produced almost as much shrinkage (in 6 cases somewhat more) as did 1 yr's drying at laboratory temperature. Indeed, if one is interested in quickly noting the relative degree of shrinkage during longer drying at normal temperature, it can be obtained by the procedure followed in securing the data of column 5. As the number of cycles of wetting and drying increased, the changes in length diminished with each cycle. Such cycles also generally resulted in the growth of the specimen. Plus signs in the seventh column indicate that the specimens were longer after the last drying than after the first, but not necessarily longer than the wet specimen before the first drying. The lengths of the specimens made from cements nos. 17, 22, and 26 were greater after the final than immediately before the first drying.

(b) COMPRESSIVE STRENGTH

The compressive strength of 2 in. cubes of mortars X, X–1, Y, and Z was studied. The amounts of water used in preparing these mortars, shown in table 2, were such that they were sufficiently workable to permit placing in the molds with a spatula. The filled molds were placed in a damp closet for 48 hr, after which the molds were removed. The specimens remained in the damp closet for 5 days longer, when the 7-day specimens were tested. The remaining specimens were then stored under water for a week. At that time one-half were removed and stored in air until tested, the other half remaining in the water. Three cubes after storage in the air and 3 after storage in water were tested at each of the following ages, 28 days, 3 mo and 1 yr.

Table 4 exhibits the compressive strengths. For the sake of brevity alone, the strengths of the mortars are presented as falling within certain groups. Such a presentation does not bring out clearly the effect of different amounts of water used in mortars X and X–1 or the gain in strength with age. But the masonry cements act like portland cements as far as increased amounts of water are concerned, and as the amount of water increases the strength decreases. Thus, while 8 of the cements in mortar X at 7 days gave strengths placing them in the highest class when the low percentage of water was used, but 3 were in this class when the high percentage was employed.

Cements with large proportions of portland cement gave mortars having greater strengths than those with small proportions, and such cements as hydraulic limes, while having little strength at early ages, increased in strength with time proportionately more than most of the others. It is evident that a wide variety of compositions may be used and good strengths obtained.

All cements in all the mortars showed good gain in strength with age, with the exception of a very few extremely high in hydrated lime. The rate of carbonation of such cements under the condition of storage was too low to be reflected in the strength at the ages at which tests were made. According to the table, the cements initially in group 7 appeared not to have gained strength with age. This is due solely to the fact that any mortar having a compressive strength over 2,000 lb/in.^{2} at any time would be shown as being in that group. Air storage usually gave higher strengths than water storage. The mixed sand of mortar X–1 produced mortars of greater strengths than the standard sand of mortar X.

TABLE 4.—*Results of compressive strength tests*

For brevity the strengths of the mortars are indicated as being within the following groups:

Groups	1	2	3	4	5	6	7
Failed (lb/in.^{2})	0 to 100	100 to 300	300 to 500	500 to 1,000	1,000 to 1,500	1,500 to 2,000	Over 2,000

[All specimens remained in molds for 48 hours, then in the damp closet for 5 days, after which they were stored either in water or in air]

Cement number	Mortar X																					Mortar X-1						
	1 percent less water than normal flow							N=percent water for normal flow							1 percent more water than normal flow							1 percent less water than normal flow						
	Water storage				Air storage			Water storage				Air storage			Water storage				Air storage			Water storage				Air storage		
	7 da	28 da	3 mo	1 yr	28 da	3 mo	1 yr	7 da	28 da	3 mo	1 yr	28 da	3 mo	1 yr	7 da	28 da	3 mo	1 yr	28 da	3 mo	1 yr	7 da	28 da	3 mo	1 yr	28 da	3 mo	1 yr
1	1	2	2	4	2	3	3	1	2	2	3	2	3	4	1	2	2	3	2	2	2	2	2	3	4	3	3	4
2	3	3	4	4	4	5	5	3	3	4	4	4	5	3	3	4	4	4	4	4	5	3	4	4	4	4	5	6
3	2	3	4	5	3	4	5	2	3	4	5	3	4	5	2	3	4	5	3	4	4	2	4	5	6	4	5	5
4	3	4	4	6	4	5	5	3	4	4	5	4	5	5	3	3	4	5	4	4	4	4	4	5	6	5	5	5
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6	4	7	6	7	5	7	6	5	7	7	7	7	7	7	5	6	6	7	6	7	7	5	6	7	7	7	7	7
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8	7	7	7	7	7	7	7	7	7	7	7	7	7	7	6	7	7	7	7	7	7	7	7	7	7	7	7	7
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12	3	4	6	7	5	5	5	2	4	6	7	5	5	6	3	4	5	5	5	5	5	3	4	6	6	5	6	6
13	1	2	4	4	2	3	3	1	2	3	3	2	2	3	1	2	3	3	2	2	2	1	3	4	4	3	4	3
14	5	5	7	7	6	7	7	4	5	6	7	6	7	7	4	5	6	7	5	7	7	4	6	7	7	6	7	7
15	2	4	4	5	4	5	5	2	4	4	5	4	4	5	2	3	4	5	4	4	5	3	4	5	4	4	5	5
16	4	5	6	7	6	6	6	4	4	5	6	4	5	6	3	4	4	6	4	5	5	5	5	6	7	5	6	7
17	3	4	4	4	4	5	5	3	3	4	4	4	5	3	3	4	4	4	4	5	5	3	3	4	4	4	4	4
18	5	7	7	7	7	7	7	5	6	7	7	7	7	7	4	6	7	7	7	7	7	5	7	7	7	7	7	7
19	7	7	7	7	7	7	7	7	7	7	7	7	7	7	6	7	7	7	7	7	7	7	7	7	7	7	7	7
20	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
21	3	3	4	4	4	4	4	3	3	4	4	4	4	4	2	3	3	4	4	4	4	3	4	4	4	4	4	4
22	4	5	5	6	6	6	7	4	4	5	5	5	6	7	4	4	5	6	5	6	6	5	5	6	6	6	7	7
23	2	4	4	5	4	4	5	3	4	4	5	4	4	5	2	4	4	5	4	4	4	3	4	4	5	4	5	5
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25	3	4	4	4	4	5	5	3	3	4	4	4	4	4	2	3	3	4	4	4	4	3	4	4	4	4	5	5
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27	4	4	5	5	5	5	6	3	4	4	5	5	5	5	4	4	4	5	5	5	5	4	5	5	6	6	6	6
28	7	7	7	7	7	7	7	7	7	7	7	7	7	7	6	7	7	7	7	7	7	7	7	7	7	7	7	7
29	1	1	3	4	1	2	2	1	1	3	3	1	2	2	1	1	3	4	1	1	2	1	2	3	4	2	3	4
30	3	4	4	4	4	4	5	2	3	4	4	4	4	5	2	3	4	4	4	4	4	2	4	4	4	4	5	5
31	7	7	7	7	7	7	7	7	7	7	7	7	7	7	6	7	7	7	7	7	7	7	7	7	7	7	7	7
32	7	7	7	7	7	7	7	6	7	7	7	7	7	7	6	6	6	7	7	7	7	7	7	7	7	7	7	7
33	4	4	5	6	4	5	6	3	4	4	5	4	4	5	3	4	4	5	4	4	5	4	4	5	5	4	5	6
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35	6	7	7	7	7	7	7	5	6	7	7	7	7	7	5	6	7	7	7	7	7	6	7	7	7	7	7	7
36	5	6	5	7	6	6	7	4	5	6	5	6	7	6	4	4	5	5	5	6	6	5	6	6	6	7	7	7
37	2	2	2	3	3	3	4	2	2	2	2	3	3	4	2	2	2	2	2	2	3	2	2	2	2	3	3	2
38	6	7	7	7	7	7	7	6	7	7	7	7	7	7	6	7	6	7	7	7	7	7	7	7	7	7	7	7
39	1	2	2	3	2	2	3	1	1	2	3	2	2	2	1	1	2	2	2	2	2	1	2	2	3	2	2	2
40	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
41	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
Group	Number of different cements falling within each group																											
1	6	1	0	0	1	0	0	5	2	0	0	1	0	0	5	2	0	0	1	1	0	3	0	0	0	0	0	0
2	5	4	3	0	2	3	1	7	5	3	1	3	3	2	9	6	3	2	4	4	4	7	4	2	1	2	1	2
3	8	6	2	3	4	3	4	8	7	4	5	6	3	6	7	6	6	3	4	1	2	8	5	3	2	4	4	1
4	7	10	12	11	12	6	5	6	9	13	8	10	9	5	8	10	12	8	11	12	9	4	11	10	12	11	5	6
5	4	6	6	4	3	9	9	6	5	2	8	4	8	7	3	4	4	10	7	5	7	7	5	5	2	4	9	8
6	3	1	5	4	7	4	4	2	2	6	3	4	2	4	6	4	6	4	2	4	4	2	4	7	7	6	3	4
7	8	13	13	19	12	16	18	7	11	13	16	13	16	17	3	9	10	14	12	14	15	10	12	14	17	14	19	20

TABLE 4.—*Results of compressive strength tests*—Continued

For brevity the strengths of the mortars are indicated as being within the following groups:

Groups	1	2	3	4	5	6	7
Failed (lb/in.²)	0 to 100	100 to 300	300 to 500	500 to 1,000	1,000 to 1,500	1,500 to 2,000	Over 2,000

[All specimens remained in molds for 48 hours, then in the damp closet for 5 days, after which they were stored either in water or in air]

Cement number	Mortar X-1—Continued														Mortar Y							Mortar Z						
	N=percent water for normal flow							1 percent more water than normal flow																				
	Water storage				Air storage			Water storage				Air storage			Water storage				Air storage			Water storage				Air storage		
	7 da	28 da	3 mo	1 yr	28 da	3 mo	1 yr	7 da	28 da	3 mo	1 yr	28 da	3 mo	1 yr	7 da	28 da	3 mo	1 yr	28 da	3 mo	1 yr	7 da	28 da	3 mo	1 yr	28 da	3 mo	1 yr
1	1	2	3	4	2	4	4	1	2	3	3	3	3	2	1	1	2	2	2	2	2	1	1	2	2	2	2	2
2	3	4	3	5	5	5	4	3	4	4	4	4	5	5														
3	2	3	3	5	4	4	4	2	3	4	5	4	4	5	1	1	2	3	2	2	2	2	3	4	4	4	4	4
4	3	4	5	6	4	5	5	3	5	4	6	4	5	5	2	3	3	4	3	3	3	4	5	5	5	4	5	5
5	4	5	5	7	6	7	7	4	5	6	6	5	6	7	2	3	3	4	3	4	4	4	5	6	6	6	7	6
6	5	6	7	7	7	7	7	5	5	7	7	6	7	7	3	4	5	5	5	5	5	5	7	7	7	7	7	7
7	2	3	3	5	3	4	4	2	3	4	5	3	4	3	1	2	4	4	2	3	3	2	3	4	5	3	4	4
8	7	7	7	4	7	7	7	7	7	7	7	7	7	7	5	6	7	7	7	7	7	6	7	7	7	7	7	7
9	3	4	3	4	5	5	4	3	4	4	4	5	5	3	2	2	2	3	2	2	2	3	4	4	3	4	4	4
0	4	5	6	7	5	7	7	4	5	6	6	6	6	6	3	4	4	5	4	4	4	4	5	6	6	5	6	5
11	2	3	4	4	3	3	4	2	2	4	4	3	3	3	2	2	2	3	2	2	2	2	2	3	3	2	3	2
12	3	4	6	6	5	6	5	3	4	6	7	5	6	5	2	3	4	4	3	4	4	3	5	7	7	6	7	7
13	1	3	4	4	3	3	4	1	3	3	3	3	2	3	1	2	2	3	2	2	2	1	2	2	2	2	2	2
14	4	5	7	7	7	7	7	4	5	6	7	6	7	7	2	3	3	4	4	4	4	5	6	7	7	7	7	7
15	3	4	3	6	4	5	5	2	4	4	5	4	5	6	2	3	4	4	3	4	3	2	3	3	4	3	4	3
16	4	5	5	6	5	5	5	4	4	5	6	5	5	6	2	2	3	4	3	3	3	2	3	4	4	3	3	4
17	3	3	4	5	4	5	4	2	3	4	4	4	4	4	1	2	2	2	2	2	2	3	4	4	4	4	5	5
18	5	7	7	7	7	7	7	5	7	7	7	7	7	7	3	4	5	6	7	7	6	6	7	7	7	7	7	7
19	7	7	7	7	7	7	7	7	7	7	7	7	7	7	6	7	7	7	7	7	7	7	7	7	7	7	7	7
20	7	7	7	7	7	7	7	7	7	7	7	7	7	7	6	7	7	7	7	7	7	7	7	7	7	7	7	7
21	2	3	4	4	4	4	4	2	3	4	4	4	4	4	2	2	2	2	2	2	2	2	3	4	4	4	4	4
22	5	4	6	6	3	7	7	4	4	5	6	4	6	6	2	3	3	3	3	4	4	5	6	6	7	7	7	7
23	3	4	4	5	4	4	4	3	4	4	5	4	4	5	2	3	4	4	2	3	2	4	5	5	6	5	5	6
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25	3	3	4	4	4	5	5	3	3	4	4	4	4	4	2	2	2	3	3	3	3	2	2	3	3	4	3	4
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31	7	7	7	7	7	7	7	6	7	7	7	7	7	7	6	7	7	7	7	7	7	5	6	7	7	7	6	7
32	6	7	7	7	7	7	7	6	7	7	7	7	7	7	4	4	5	5	5	5	5	7	7	7	7	7	7	7
33	3	4	5	5	4	5	5	3	4	4	5	4	4	4	2	3	4	5	3	4	4	3	4	4	5	4	5	5
34	5	5	6	6	6	7	7	5	5	5	6	6	6	7	3	3	3	4	4	4	4	6	6	7	7	7	7	7
35	6	7	7	7	7	7	7	5	5	7	7	7	7	7	4	5	5	5	5	5	5	6	7	7	7	7	7	7
36	4	6	6	6	6	7	6	4	5	5	5	6	6	5	4	4	4	4	5	5	5	3	4	4	4	4	4	4
37	2	2	2	2	3	3	3	2	2	2	2	2	3	2	1	1	1	1	1	1	1	2	2	2	2	3	3	3
38	7	7	7	7	7	7	7	6	7	7	7	7	7	7	5	6	6	6	6	6	7	5	6	6	7	6	6	7
39	1	2	2	3	2	2	2	1	1	2	3	2	2	2	1	1	1	2	1	2	2	1	2	2	3	2	2	3
40	7	7	7	7	7	7	7	7	7	7	7	7	7	7	6	7	7	7	7	7	7	6	7	7	7	7	7	7
41	7	7	7	7	7	7	7	7	7	7	7	7	7	7	6	7	7	7	7	7	7	6	7	7	7	7	7	7
Group	Number of different cements falling within each group																											
1	4	1	0	0	1	0	0	4	2	0	0	1	1	0	10	6	2	1	3	2	2	4	1	0	0	1	0	0
2	7	3	2	1	2	2	2	9	4	2	1	2	2	4	14	9	11	6	11	10	10	9	7	4	3	5	4	4
3	9	9	8	1	6	3	1	7	6	4	4	4	3	4	4	10	7	7	7	5	6	5	5	5	4	4	4	3
4	6	9	7	10	9	7	11	7	10	13	8	12	9	6	4	5	7	11	5	9	8	6	4	8	8	8	7	8
5	4	5	5	7	6	9	8	5	9	5	7	5	5	6	2	2	4	5	5	4	5	7	6	2	4	2	4	5
6	5	2	5	7	3	1	1	3	0	4	6	5	7	5	6	2	2	3	1	2	1	6	7	5	4	5	4	3
7	6	12	14	15	14	19	18	6	10	13	15	12	14	16	0	6	7	7	8	8	8	3	10	16	17	15	17	17

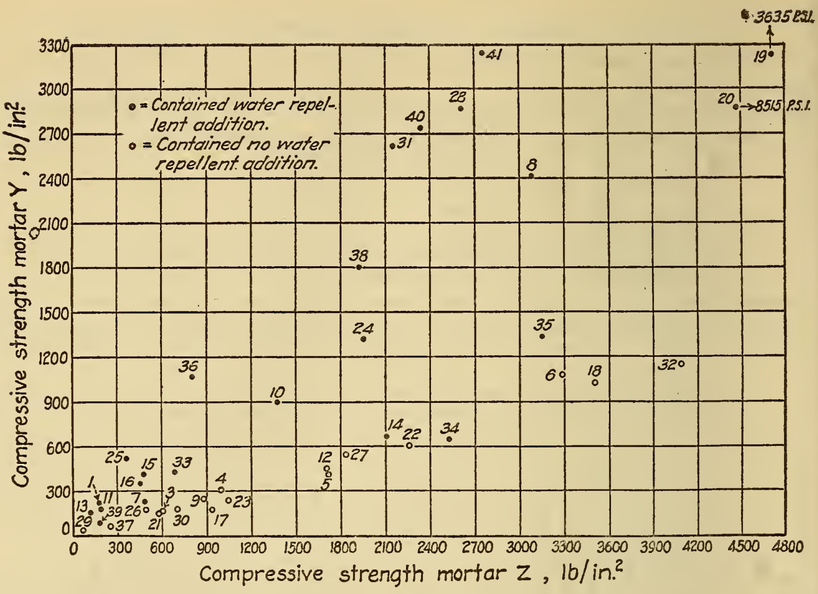

FIGURE 16.—*Relation between 28-day compressive strength of mortars* Y *and* Z *at normal flow.*

Two-inch cubes stored in damp closet 7 days at 21° C, then 7 days submerged in water, then 14 days in air at 21° C, 60±5 percent relative humidity.

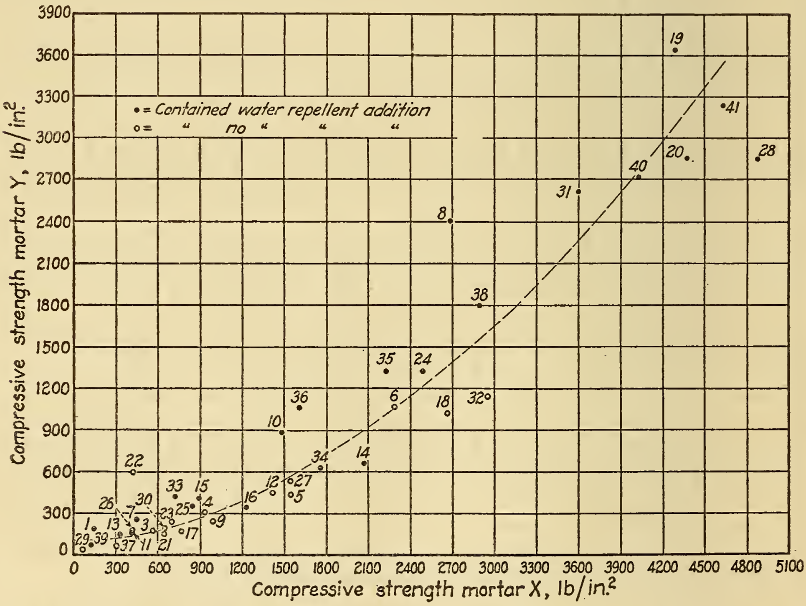

FIGURE 17.—*Relation between 28-day compressive strength of mortars* X *and* Y *at normal flow.*

Two-inch cubes stored in damp closet 7 days at 21° C, then 7 days submerged in water, then 14 days in air at 21° C, 60±5 percent relative humidity.

While in a general way it might be said that the mortars of the Y type had less strength than those of the X or the X–1 types, and that mortar Z was between these types, some interesting relations can be noted on comparing figures 16 and 17. In the former figure the strengths of the air-stored specimens at 28 days of mortars Y and Z are presented. The classification of the mortars of the water-repellent and nonwater-repellent cements is again evident with the usual few exceptions. Mortars of the Z type tend to have strengths somewhat greater than those of the Y type; again those of the Z type not containing the water-repellent additions are 3 to 4 times as strong as those of the Y type at 28 days. All mortars X without water-repellent cements except no. 22 are within the range of 2 to 4 times the strength

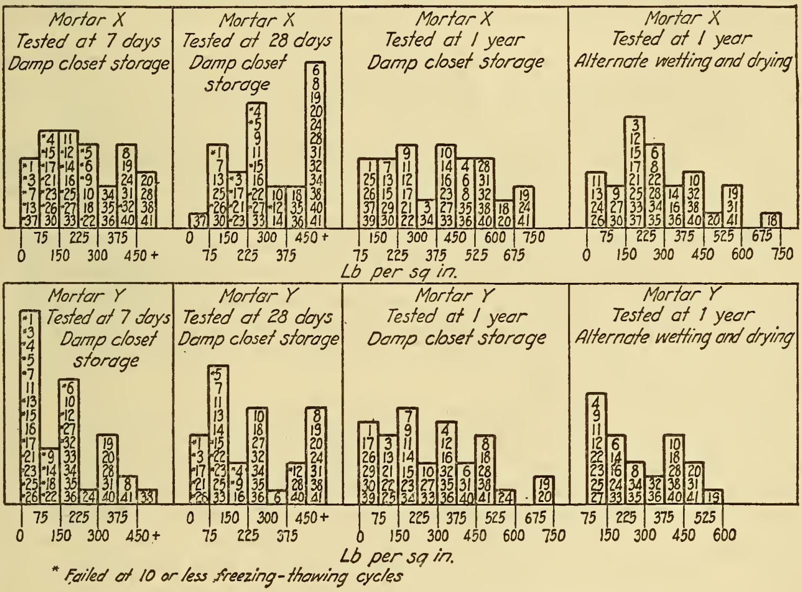

FIGURE 18.—*Moduli of rupture mortars X and Y.*

Cement no. 2 not tested in any storages shown; cement no. 5 not tested in the cases of 1-year damp closet, nor alternate wetting and drying because the supply of the cements was exhausted. Specimens made from other cements not represented in these histograms broke during storage.

of mortars Y, while only 7 of those with water-repellent cements are within that range. All but 7 of the first class are within the range 3 or 4 times as strong. The explanation can possibly be found by consulting tables 1 and 2 and noting the volume weights of the cements and the weight proportions of the mortar. The Z mortars made from nonwater-repellent cements were usually richer in cement than those made of the water-repellent ones. This resulted from the differences in the bulk specific gravities of the neat pastes.

Figure 17 shows the relation between the compressive strength at 28 days' air storage of the cements when used in mortars X and Y. Here it will be noted that the relation is markedly different from that exhibited in comparing mortars Y and Z (fig. 16). Mortar X was proportioned on a 1:3 by weight basis and mortar Y on a 1:3 by volume. Hence it will be noted that when the cements had low weight per cu ft the cements in mortar X developed approximately 3 times

the strength which they produced in mortar Y, but as this weight increased the 1:3 volume mortars approached the same weight ratio as used in mortar X and the strengths more nearly approached one another. The portland cements or those having a large proportion of portland cement gave mortars of nearly equal strengths.

(c) TRANSVERSE STRENGTH

Specimens of mortars X and Y, 1 by 4 by 12 in., were tested flatwise for transverse strength with a center load on a 10-in. span, the load being applied on the top of the specimen as cast. These were proportioned as shown in table 2 for normal flow. The curing conditions and results of tests are given in figure 18. The molds were removed at 24 hr or as soon thereafter as possible. Specimens of cement no. 29 had not hardened at 28 days sufficiently to be included in these tests.

The strengths for the type X mortars of the several cements are, with a very few exceptions, higher than for the type Y. This is due to the former having been made on a 1:3 by weight basis and, therefore, richer in cement than the latter, which are proportioned on a 1:3 by volume basis. As noted in discussing the compressive strengths, those cements rich in portland cement tended to give mortars with the higher strengths.

The increase in strength in 1 year with alternate wetting and drying was not as great as when the specimens were stored continuously in the damp closet. Those having the greatest linear change showed the greatest difference. The exceptions were some of the specimens made from cements composed entirely or largely of portland cement and the one of hydrated lime.

Figure 19 has been prepared to show the relation between the 7- and 28-day transverse and compressive strengths of mortar Y when the 28-day compressive strength specimens were stored for the last 21 days of their aging in water. The trend indicated is that usually shown by other materials—the greater the compressive strength, the greater the modulus of rupture. However, the ratio between the two varies considerably. Those below a compressive strength of 900 lb/in.^{2} have a transverse strength of somewhat less than one-third of the compressive strength, while above 900 lb/in.^{2} the values change until at the higher strength the ratio is approximately 1:6. The compressive strengths for the majority of the specimens of mortar Y tested both at 7 and 28 days were below 900 lb/in.^{2} and the modulus of rupture below 300 lb/in.^{2}

(d) DURABILITY IN FREEZING AND THAWING TESTS

One of the halves of each specimen remaining after the transverse tests were made, at both 7 and 28 days, was submitted to freezing and thawing cycles. One cycle consisted in freezing for 24 hr, flatwise in about ½ in. of water, followed by 24 hr of thawing in water at room temperature. The results are presented in table 5.

It is seen that there is little difference in the destructive action of freezing and thawing on the rich mortar X and on the leaner mortar Y. Comparing these results with the compressive and transverse strengths it was noted that those mortars which had a low strength, or low modulus, with the exception of the specimen made of cement no. 11, showed poor resistance. As previously noted, the higher strengths generally resulted when the mortars contained cements rich in portland cement.

Aging the specimens until 28 days before starting the freezing and thawing, instead of but 7 days, permitted a few of the mortars to

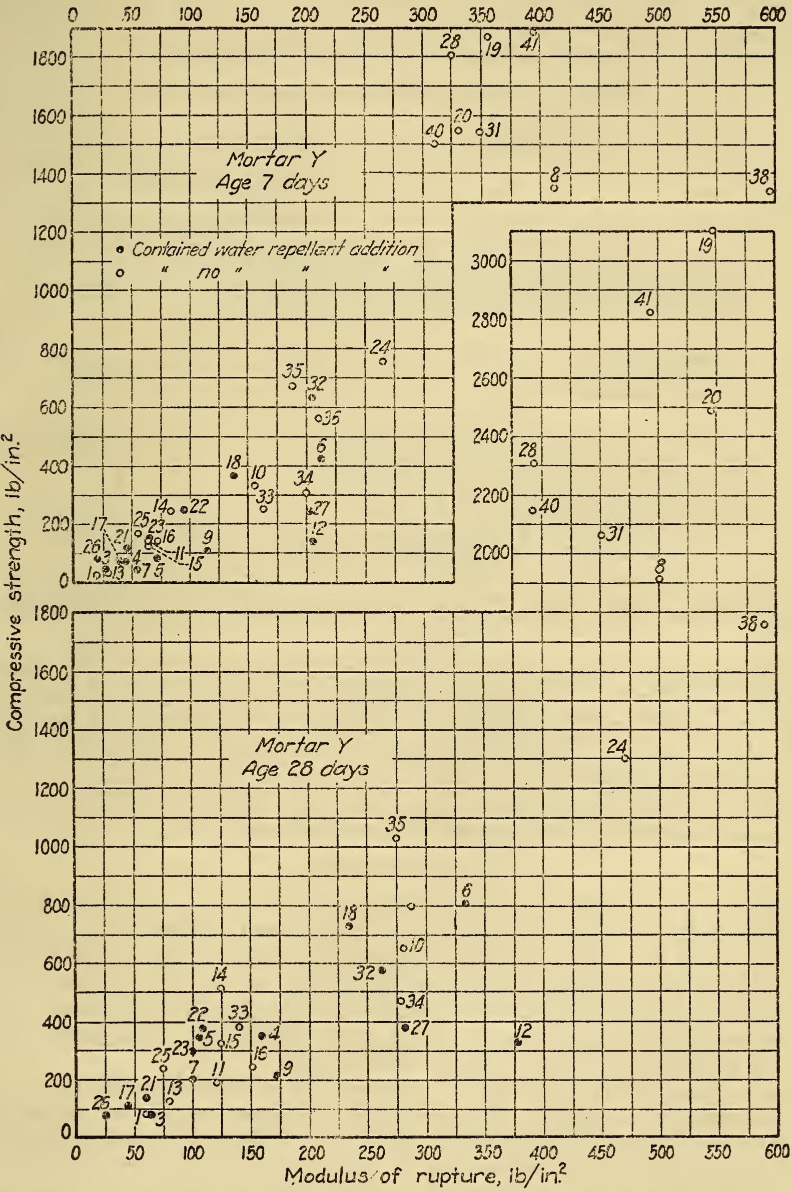

Figure 19.—*Relation between compressive strength and modulus of rupture for mortar* Y.

All 2-inch cubes for compressive strength were stored in the damp closet at 21° C for 7 days. The 28-day specimens were stored in water at 21° C for 21 days. The specimens for transverse tests were stored continuously until breaking date in the damp closet at 21° C.

develop better resistance. Such usually showed good compressive strength gains between 7 and 28 days. A surprising feature of these

tests is that relatively few specimens were in the group that failed between 10 and 300 cycles. Most of the mortars had either a very poor or a good resistance to the destructive action of freezing and thawing.

TABLE 5.—*Results of freezing and thawing tests*

[Specimens 1 by 4 by 6 in. made from mortar gaged to normal flow]

Materials		Days in damp closet	Failed
Mortar	Cement		
			(*Cycles*)
X	1, 3, 4, 5, 6, 7, 9, 12, 13, 14, 15, 17, 21, 22, 23, 25, 26, 27, 29, 32, 37, 39	7	10 or less.
Y	1, 3, 4, 5, 6, 7, 9, 12, 13, 14, 15, 17, 18, 21, 22, 23, 25, 26, 27, 29, 30, 32, 37, 39		
X	1, 3, 4, 5, 12, 15, 17, 21, 22, 23, 26, 27, 29, 30, 37, 39	28	
Y	1, 3, 4, 5, 9, 12, 15, 17, 21, 22, 23, 26, 29, 30, 37, 39		
X	18, 30, 33	7	Between 10 and 100.
Y	16, 20, 33, 35		
X	6, 9, 13, 18, 25, 32, 33	28	
Y	6, 13, 14, 16, 18, 25, 27, 32, 33		
X	19, 20	7	Between 100 and 250.
Y	19, 34		
X	14	28	
Y	19		
X	8, 10, 11, 16, 24, 28, 31, 34, 35, 36, 38, 40, 41	7	Over 250.[a] No failures.
Y	8, 10, 11, 24, 28, 31, 36, 38, 40, 41		
X	7, 8, 10, 11, 16, 19, 20, 24, 28, 31, 34, 35, 36, 38, 40, 41	28	
Y	7, 8, 10, 11, 20, 24, 28, 31, 34, 35, 36, 38, 40, 41		

[a] No specimens in this group failed—testing was discontinued when the number of cycles to which the specimens had been subjected varied from 335 to 460, the earlier-made specimens having received the larger number.

Specimens of mortar Y, stored for 28 days in the damp closet, which failed in 10 or less cycles of freezing and thawing had compressive strengths less than 400 lb/in.^{2} Only 2 having strengths less than 400 lb/in.^{2} resisted more than 100 cycles; these 2 were made from cements nos. 7 and 11.

Some further discussion of durability will be found under the next heading presenting the data on absorption tests.

(e) ABSORPTION

Halves of the specimens remaining after the transverse tests were used for the studies of absorption. These were dried in an oven at 65° C until no loss of weight during 24 hr was noted. The air was circulated during drying, part of the moist air being constantly replaced. The specimens were cooled, then immersed in water and weighed after periods of 1/12, 1/4, 1/2, 1, 3, 5, 24, and 72 hr. The percentage water absorbed in 72 hr is given in figure 20.

As a general rule, the less the amount of water to produce, with a given cement, a mortar of normal flow, the less water was absorbed by the cured mortar specimens (fig. 21). Tests of the other mortar specimens showed the same trend. Absorption tests were made only on mortars X and Y gaged to normal flow. Hence, no data are available showing how any of the cements varied in absorption when gaged with different amounts of water.

It is of interest to compare figures 22 and 13. The former presents the relation of the bulk specific gravity of mortar Y to the percentage water absorbed by the specimens of that mortar after 7 days' aging, also the results of freezing and thawing tests. (Similar relations were

found for this mortar at other intervals during absorption tests and after 28 days of aging.) Again the cements group themselves according to presence or absence of water-repellent materials. The water-repellent mortars may have a wide range in bulk specific gravity without a corresponding range in absorption, whereas in mortars lacking water-repellent materials a narrow range in bulk specific gravity is accompanied by a wide range in absorption. The porous

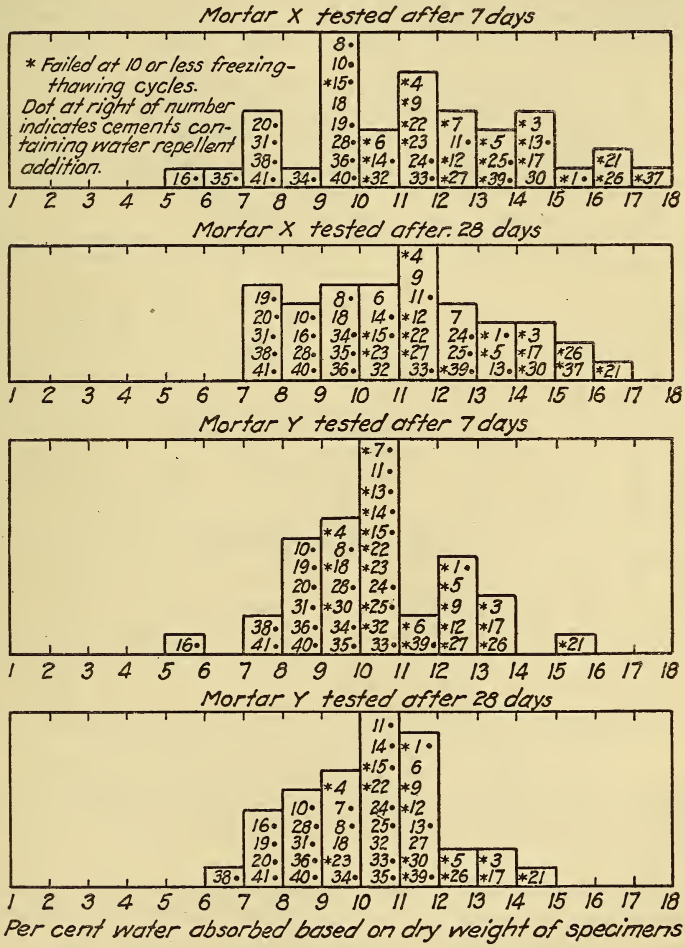

FIGURE 20.—*Absorption, 72 hours total immersion.*

Specimens made from cement no. 29, mortar X, crumbled when immersed; specimens made from cements nos. 29 and 37, mortar Y, crumbled when immersed. Cement no. 2 not shown because supply of cement was exhausted.

structure of those specimens made from mortars of a high air content, as shown in figure 13, would, in the specimens having high absorption, be expected to be disrupted with freezing. Such was not always the case. Hence, it would appear that the failures are not due solely to the expansion in the water-filled air cells during freezing, but more to the freezing of the water-saturated partially hydrated cement of the cell walls.

Kreuger[6] in a study of the weathering resistance of burned clay materials proposed the ratio of absorption at 4 days to porosity obtained by specific gravity determinations as an indication of resistance. Data for the calculation of the Kreuger ratio for the mortar specimens were not complete, but there was evidence that the water-repellent mortars had lower ratios than most of the others and their resistance was good. If the explanation in the preceding paragraph is accepted, then it is necessary to assume that the more complete filling with water prior to freezing of the very low percentage of air voids of the nonwater-repellent mortars (the average percentage

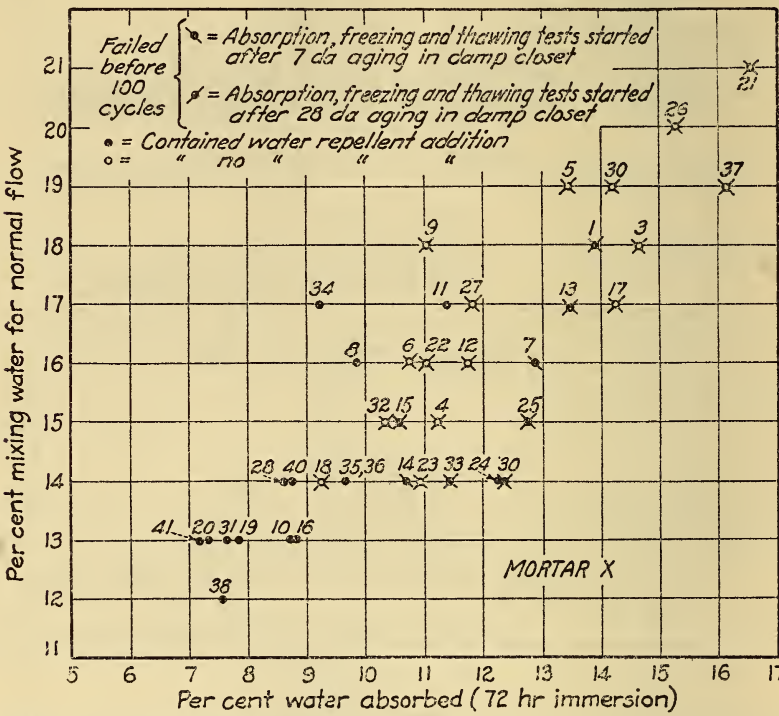

FIGURE 21.—*Relation between quantity of mixing water required for normal flow for mortar* X *and the water absorbed in 72 hours by this mortar after being aged for 28 days.*

air by volume was 3.7) was the cause of their low resistance. It would follow then that the less complete filling of the very high percentage of air voids of the water-repellent mortars (the average percentage air by volume was 19.53) was the reason for their good resistance. The voids resulting from the loss of mixing water due to hydration, evaporation, etc., are not considered here. The voids from this source were about equal for the water-repellent and nonwater-repellent mortars, although there was a slight tendency for the water-repellent mortars to require less mixing water than the others.

A study of the rate of absorption brought out the fact that the first 90 percent of the absorption at 72 hr took place relatively rapidly. All but 10 percent of the absorption in mortars X and Y had, in about

[6] Trans. Roy. Swed. Inst. Sci. Ind. Res. 24, 70 (1923).

half of the specimens, taken place in less than 1 hr. Further, as shown by figure 23, there seemed to be a relation between the time for mortars to attain 90 percent of the 72 hr absorption and the resistance to the destructive action of freezing and thawing. The poorly resisting mortars of the X and Y types have an absorption equal to 90 percent of that measured in 72 hr within ½ hr) when the determinations were made on specimens aged for 7 days, and within 1 hr when the determinations are made on the 28-day specimens. The mortars of the Y type being somewhat lean usually had a faster rate of absorp-

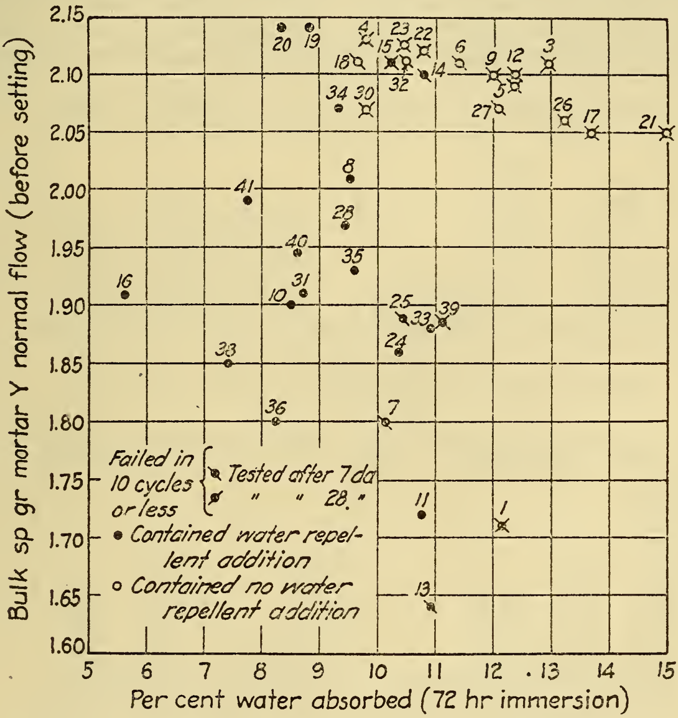

FIGURE 22.—*Relation between bulk specific gravity mortar Y and 72-hour absorption of the same mortar after being aged for 7 days.*

Specimens made from cements nos. 29 and 37 disintegrated during the test.

tion than those of the richer X type. Mortars Y made from cements nos. 11, 24, and 27, aged 28 days, are exceptions.

(f) WATER RISE DURING PARTIAL IMMERSION

After the previous weight-absorption study had been completed, the specimens were again dried to constant weight at 65° C. They were then cooled to room temperature and placed on end in ½ in. of water and the water line or height to which the specimens became wetted was measured at $\frac{1}{12}$, ¼, ½, 1, 3, 5, 24, and 72 hr. Measurements were made to the nearest 0.1 in. on both the sides which had been the top and bottom of the specimen when molded. The average of the 2 measurements was recorded.

The data are not presented here, but it was found that the linear rise in the partially immersed specimens also would serve as an indi-

cation of durability. Of those mortars with a 2-in. rise in 1 hr or less, all failed in 10 or less cycles of freezing and thawing. In 59 out of 71 cases those mortars which showed a 2-in. rise in 3 hr or less failed in 10 or less cycles of freezing and thawing. The leaner mortar Y showed a more rapid rise than mortar X, and with both types the rise at 7 days' age was more rapid than at 28 days.

(g) EFFLORESCENCE

The tendency of the cements to effloresce was studied by placing the specimens that had undergone the absorption tests on end in trays of water to the depth of ½ in. Observations made at the end of 3 months after the storage period started appeared to represent the

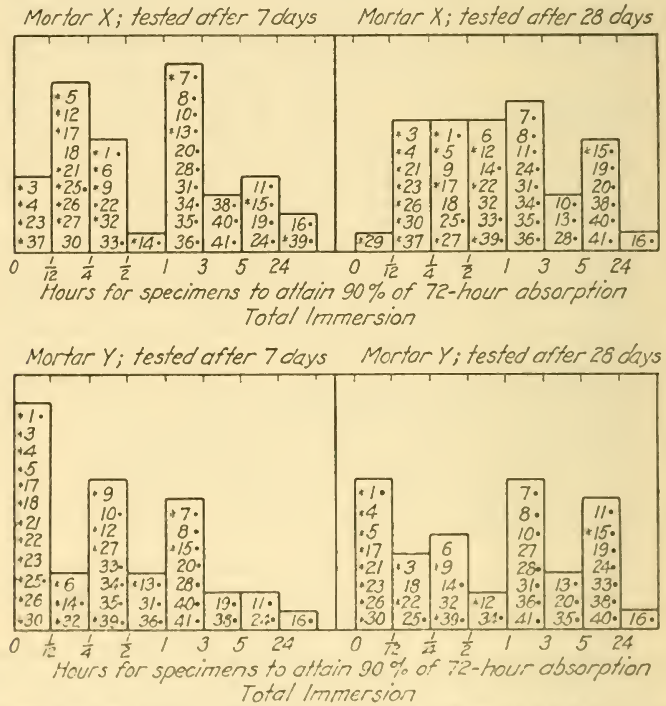

FIGURE 23.—*Time required for mortars to attain 90 percent of the 72-hour absorption.*

* Failure of specimens in 10 or less freezing-thawing cycles. Dot at right of numbers indicates cements containing water-repellent addition.
Specimens were 1 by 4 by 6 in.

maximum condition of efflorescence. Slight efflorescence was noted with:

Cements nos.[7] 11 (b), 12 (e), 13 (b), 24 (b), and 39 (d) of mortar X subjected to test after 7 days' aging;

Cements nos. 8 (a), 12 (e), 13 (b), 24 (b), and 31 (a) of mortar X subjected to test after 28 days' aging;

Cements nos. 9 (e), 11 (b), 13 (b), 16 (b), 23 (e), 34 (d), and 39 (d) of mortar Y subjected to test after 7 days' aging;

Cements nos. 5 (e), 7 (b), 13 (b), 16 (b), 23 (e), 24 (b), 30 (e), 31 (a), and 39 (d) of mortar Y subjected to test after 28 days' aging.

[7] Letters in parentheses refer to water-repellent additions. See table 1 for legend.

NOTE

The two closing sentences of section "(g) Efflorescence," page 845, Research Paper 746, should read:

the number and description of the cements that effloresced slightly or pronouncedly are as follows:-

one of the seven classed as "largely portland cement,"
two of the two classed as "portland cement and natural cement,"
three of the eight classed as "portland cement and lime,"
two of the ten classed as "portland cement and unidentified material,"
none of the two classed as "hydraulic or hydrated lime,"
four of the four classed as "natural cement,"
two of the six classed as "large amounts of slag,"
one of the two classed as "composition unidentified."

Pronounced efflorescence was noted with:

Cements nos. 1 (a) and 7 (b) of mortar X subjected to test after 7 days' aging.

Cements nos. 1 (a), 7 (b), and 11 (b) of mortar X subjected to test after 28 days' aging;

Cements nos. 1 (a), 5 (e), and 7 (b) of mortar Y subjected to test after 7 days' aging;

Cements nos. 1 (a) and 11 (b) of mortar Y subjected to test after 28 days' aging.

The other cements did not develop efflorescence in either mortar.

Efflorescence developed through such a test depends upon the composition of the cement. But again, owing to the heterogeneous nature of the cement, it is difficult to draw any positive conclusions as to the rate of solution of any of the components of the cement and their deposition on dry parts of the mortar. It will be noted that cements 5, 9, 12, 23, and 30 did not have water-repellent materials, while cements nos. 1, 7, 11, 13, 16, 24, 31, 34, and 39 had such additions. All except no. 5 of those showing pronounced efflorescence had water-repellent additions. All cements containing natural cement, 1 portland cement, 1 of portland cement and lime, 2 of the 4 slag cements, 2 of the unidentified composition effloresced. No efflorescence was observed with cements nos. 3 and 37.

V. DISCUSSION

The number of tests required by specifications for masonry cements should be held to a minimum and confined to those that can be completed in a relatively short time. It is, therefore, desirable to study the essential properties to find possible correlations between them and to see if the measurement of one will give an indication of another. Among the properties that are of interest are workability, durability, strength, absorption, linear changes during and after hardening, water-retaining capacity, volume yield of mortar, and range in water content of workable mortar. These properties have been enumerated without regard to their relative importance.

Two of these properties—durability and linear change—can be determined only by tests that require a longer time than would be convenient for an acceptance test. There seems to be no relation between the linear changes and the other properties of the mortars. While but a small change is desirable, the data are not conclusive enough to indicate the maximum amount permissible, although they indicated that the changes were so large as to be a matter of some concern. Although the changes during setting seem large, these changes might be neglected if they take place before rigidity is acquired by the mortar. The cracks frequently noted in vertical joints of masonry between the mortar and the brick or stone might be due in part to the large change in volume of the mortar during setting, or to stresses set up during that period which with subsequent slight contraction would yield cracks. But further work should be done in the study of this problem, and it is a question if it should not be an item in all cement specifications.

Durability as measured by the freezing and thawing tests may be predicted with fair accuracy from the rate of absorption of specimens 1 by 4 by 6 in. aged 28 days, and with less assurance with those aged

7 days. The absorption at 28 days is, therefore, suggested as a specification requirement for the indication of the durability. A requirement that the 1 hr absorption of a 28-day-old mortar shall not exceed 90 percent of the 72 hr absorption will, in the majority of cases, eliminate those cements which would make a mortar that will not endure 10 or more cycles of freezing and thawing.

The modulus of rupture and the compressive strength have sufficient relation to one another to permit the use of only one of these criteria as a measure of the strength. By reason of the relative ease of fabricating and testing, the 2-in. cube made of graded sand, of 1:3 proportion by weight at approximately normal flow, is suggested as a test specimen.

The strength that should be required is a matter of conjecture. A moderate or even a low strength would be sufficient in many cases. But in masonry construction where hollow thin walled units are used, a high-strength mortar is essential. It might be desirable to have 2 classes of strength—a higher and a lower one—and permit the specification writer to indicate that which he feels is required. In such a case, the lower strength requirement might have a minimum of 250 lb/in.^{2} at 7 days, and 400 at 28 days, and the higher demand a strength of 1,000 lb/in.^{2} at 7 days, and 1,500 at 28 days.

Mortars should retain their workability for a short time while in contact with a dry brick of moderately fast rate of absorption. The workability characteristics should be determined by studying the properties, stirring resistance, and water-retaining capacity together. For example, mortars made from cements that have a wide water-range could be prepared with the greater proportions of mixing water so that the mortars would retain their workability when exposed to absorptive units, or cements that have a narrow water range and yet have a sufficiently high water-retaining capacity to remain in the workable range. It was observed that the cements that required small amounts of water for the desired degree of workability and retained their workability in the presence of an absorptive unit usually had other good characteristics. In view of the unusual equipment needed to measure these two properties, it is suggested that this should be a subject for further consideration. The cements tested that retained not less than 0.9 and 0.85 of the mixing water at normal flow for 1 and 3 min. of suction, respectively, retained a satisfactory workability.

The volume yield of the mortar is primarily of economic importance. But it is so much influenced by the amount of occluded air that even though the air has a markedly favorable influence on workability and no deleterious effect on durability, it might seem to be desirable to have a maximum limit on the yield.

Observations in actual service of products bonded by hydraulic cements show that the denser products have greater life. There is no correlation at present between service results and laboratory data, therefore no limits are proposed for the amount of occluded air.

The majority of these masonry cements have been on the market for this purpose but a relatively short time. Their development seems to have been largely empirical, and it is believed that some of the methods of study used in this investigation would be of value to manufacturers in improving their products. Thus, the measurement of the water range within the limits of high and low stirring resistance would be of value when considered in conjunction with the water-

retaining capacity. If these properties are not satisfactory, he can be assured that his product is not on a parity with cements of wider adaptability.

The manufacturer should consider the several phases of workability. Does his cement give workable mortars with high percentages of water or with low? Is such workability accompanied by a large or small inclusion of air? Has the acquiring of workability been accompanied by lower strengths? What are the nature and economy in the use of the agent added to secure workability? These and other items are of much importance in the development of cements for setting masonry, and through their study it seems very likely that such cements will approach much more closely standard products of rather similar nature and properties than at the present time.

The composition of masonry cement seems to be the feature most affecting durability to freezing and thawing, although the effect of the varying proportions of water used in making the mortars was not studied. That is, the durability test was not carried out on mortars where the water-cement ratio alone varied. But as noted in the discussion of strength, those mortars requiring high amounts of water for normal flow have in the majority of cases lower strengths than those requiring the lower amounts.

It is true that producers of this commodity can point with much pride to the excellent results obtained up to the present in the matter of resistance to weathering. But too many of these cements have been on the market such a short time their true length of life has not been determined. Freezing and thawing studies should, therefore, be conducted in developing masonry cements.

The present difficulties encountered in obtaining water-tight masonry walls indicate that possibly the proper masonry cement has not yet been developed—even acknowledging that besides the cement the wall consists of a unit, the water and sand of the mortar, and the assembling of all of these. Although the linear changes found in this investigation were small relative to the total length of the specimens, field conditions seem to indicate that these changes are worthy of concern. Linear changes that may accompany the setting, hardening, and weathering are matters of consequence and producers should determine them, and how they are affected by changes in the composition of their product.

No doubt at all times the consumer will demand strength equal to or above a specified minimum. It also happens that a strength higher than the minimum of a specification is frequently used as a sales argument and accepted as evidence of an enhanced quality. The producer, therefore, is always interested in strength, but he should study this property in connection with all the others. Increased strength should not be obtained at the expense of such equally essential properties as workability, volume change, range of water content, water-retaining capacity, etc.

The majority of cements used in this study are commonly referred to as "waterproof". In this paper they have been referred to as containing "water-repellent additions". The amount of the total absorption on immersion in water as well as the rate of absorption indicates that the use of the word waterproof to describe the cements is incorrect, and even the adjective "water-repellent" is open to question. But these additions do serve to render the mortar water-shedding to

some degree. The use of the proper agents to secure this property is apparently justified, but the outstanding effect of their use seems to be that of a plasticizer. Without much doubt they do render a mortar more workable—nothing more than spreading such mortars with a trowel is needed to demonstrate that. Here again producers seem to use a wide variety of materials and have not studied their effect either as water-repellents or as plasticizers. This particular component of the cements should be studied thoroughly by all producers not only in regard to the two properties just cited, but also as to its effect on the mixing water requirements.

VI. SUMMARY

1. The cements included in the study may be grouped into the classifications, hydrated or hydraulic lime, natural cement, portland cement with or without admixtures, mixtures of portland cement and lime, portland and natural cements, portland cement with various unidentified materials, blast furnace slag with various additions, and 2 whose identity could not be established. About half of the cements contain water-repellent materials.

2. The amounts of the cements retained on a no. 450 sieve varied between 11.3 and 49.7 percent.

3. The rodded weights varied from 39.7 to 89.9 lb/ft^3; the loose weight from 32.5 to 80.6 lb/ft^3.

4. The bulk specific gravities of the neat cement pastes having a neat spread of 8 in. varied from 0.83 to 1.93, the lower specific gravities being due largely to the incorporation of air caused mainly by the presence of water-repellent materials in the cements. No correlation was found between time of flow in the neat spread test and any other property measured.

5. Mortars in the proportion of 1:3 cement-standard Ottawa sand by weight, 1:3 with mixed Ottawa sand by weight and by volume, as well as mortar with a constant ratio of 1:1.57 neat paste to mixed sand by volume were studied.

6. The water content required for workability as measured by the stirring resistance in the range of from 200 to 1,200 g was determined. The water content varied both in the amount required for maximum resistance and in the range of these amounts. The proportions of mixing water required to produce the minimum stirring resistance varied from 15.2 to 30 percent, for the maximum resistance from 9.2 to 24.2 percent. The smallest range in water content for a given cement between these limits of stirring resistance was 3 percent and the largest was 11 percent.

7. The water-retaining capacity was measured by subjecting the mortar for 1 and 3 min intervals to a suction equivalent to that of a brick of medium absorption. After 1 min of suction, from 53 to 98 percent of the water initially present in the mortar was retained. The least amount was retained by a cement largely portland, the greatest by a portalnd cement-hydrated lime mixture. In only 3 cases (cements nos. 5, 14, and 27) was there no more water extracted by the 3 min suction than by the 1 min suction. In all cases the mortars containing the maximum amount of mixing water lost more water than those mortars having the minimum amount of mixing water. Those cements containing large amounts of slag and those classified as largely portland cements lost a greater percentage of the mixing water than did those of the other classes.

8. The volume yield of mortar Y, proportioned on a 1:3 rodded volume basis, varied from 3.3 to 4.2 volumes per unit volume of cement. The larger volume yields were due to the larger volumes of air incorporated in the mortar, the increase in yield being nearly proportional to the amount of air retained. The greater amount of air was retained by mortars containing water-repellent cements. The greatest quantity of air contained by a mortar containing a non-water-repellent cement was 7.0 percent; only 2 of 23 mortars with water-repellent cements contained less than 8 percent air, only 6 less than 14 percent.

9. The shrinkage during the first 24 hr varied from 0.087 to 0.585 percent. There was little distinction between the water-repellent cements and the nonwater-repellent cements in the amount of shrinkage in 24 hr. The length changes during the year following were small in comparison to the first 24 hr shrinkage. The length changes in the first drying after removal from the damp closet were of about the same magnitude as the shrinkages in 1 yr air storage, namely, values ranging from 0.026 to 0.154 percent.

10. The compressive strengths showed an enormous range. For example, the 28 day strength of mortar Y varied from about 50 to 3,650 lb/in.^{2} The strengths of the 41 cements were scattered between these extreme values. Thirteen were below 300 lb/in.^{2}, 22 below 600 lb/in.^{2}

11. The modulus of rupture showed an approximate relation to the compressive strength; the 28 day modulus of rupture of mortar Y varied from 25 to 590 lb/in.^{2} The relation between modulus of rupture and compressive strength was sufficiently good to eliminate the necessity of including both tests in specification requirements.

12. Specimens of mortar Y, 28-day damp-closet storage, which failed in 10 or less cycles of freezing and thawing had compressive strengths less than 400 lb/in.^{2} Only 2 having strengths less than 400 lb/in.^{2} resisted more than 100 cycles; these 2 were made from natural cements.

13. The durability of the mortars when subjected to freezing and thawing tests could be predicted with reasonable accuracy by the time required for mortar specimens 1 by 4 by 6 in. aged 28 days to attain 90 percent of their 72-hr absorption. The mortar specimens, with one exception, that required more than 1 hr to absorb 90 percent of the water that would be absorbed in 72-hr were not disrupted by 10 cycles of freezing and thawing. It may be noted that the water-repellent cements are as a group more durable than the nonwater-repellent type. For example, of mortar X, aged 28 days, but 3 of the 23 water-repellent cements failed in 10 freezing and thawing cycles, whereas of the 17 nonwater-repellent cements, 13 failed in 10 freezing and thawing cycles.

14. The linear rise of water in the specimens also gives an indication of their durability. In 59 of 71 cases, those mortars with a rise of 2 in. in 3 hr or less failed in less than 10 freezing and thawing cycles. Of those with a 2-in. rise in 1 hr or less, all failed in 10 cycles or less.

15. Some cements did not develop efflorescence; in the others from a slight to a pronounced efflorescence was noted.

16. A discussion of some of the essentials of specifications for masonry cement is given, with suggested limits for the several tests.

WASHINGTON, September 21, 1934.